Sveriges lantbruksuniversitet
Swedish University of Agricultural Sciences

Institutionen för energi och teknik

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Civilingenjörsprogrammet i energisystem

Examensarbete 2014:10
ISSN 1654-9392
Uppsala 2014

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EX0724, Degree Project in Energy Systems Engineering, 30 credits, Technology, Advanced level, A2E
Master Programme in Energy Systems Engineering (Civilingenjörsprogrammet i energisystem)

Series title: Examensarbete (Institutionen för energi och teknik, SLU)
ISSN 1654-9392
2014:10

Uppsala 2014

Keywords: biogas, efficiency, small-scale, manure, performance, insights

Online publication: http://stud.epsilon.slu.se

Cover: The Grinstad biogas plant's digestion chamber, 2013. Photo by author.

Abstract

Energianalys av gårdsbaserade biogasanläggningar i Sverige

Energy analysis of farm-based biogas plants in Sweden

Erik Parmlind

It is projected that energy demand worldwide will double from 2009 until 2050. There is a demand for additional clean renewable energy, which can be supplied by biogas. Farm-based biogas plants exist in small numbers in Sweden; for the benefit of society it important to increase their numbers throughout the country. The aim of this report is to create the tools to allow for a competent evaluation of newly built farm-based biogas plants from an energy efficiency and environmental perspective.

In this thesis data from newly built plants has been analyzed to determine mistakes that could be avoided in future expansion. Research has been performed within the bounds of a SLF financed project focusing on the role of cooperation in achieving profitability and environmental benefits in farm based biogas plants

The thesis has found that the investment cost during the technical lifetime of the plant is 11-16 kWh/MWh and 2.65 – 3.65 kg CO_2-eq. per MWh. The initial investment is repaid by a factor of at least 50 during the technical lifetime of the plant.

Energy ratios have been calculated for two of the plants that express the usable energy produced from each. It has been found that 29 % of Högryd's 2 GWh in energy production becomes usable electricity and heat; at Lövsta 62 % of its 10 GWh became usable electricity and heat. A larger biogas plant benefits from a higher electrical efficiency, however, the impact of the heat utilization is significant. Replacement of 120 MWh of oil and electricity reduces the import of fossil-fuels more than 1.5 GWh of wood chips.

Sammanfattning

Energianalys av gårdsbaserade biogasanläggningar i Sverige

Det finns en förväntning att världens energibehov kommer att fördubbla från 2009 till 2050. Redan nu inser världen problemet med växthusgasutsläpp och vikten av att begränsa energitillförseln från icke-förnyelsebara källor. Därigenom skapas ett ökande behov av förnyelsebar energi, utan större påverkan på lokal och global miljö.

Biogas har blivit populärt i Sverige under gångna decennier och biogasverk finns i flertalet av svenska städer. Det är även intressant på en gårdsbaserad nivå, då många lantbrukare har ett intresse att tillvarata den energipotential som finns i gödsel och andra substrat.

Gårdsbaserade biogasanläggningar i Sverige är få till antalet. Men för samhället i stort är det viktigt att kunna utnyttja varje möjlig energikälla och därigenom utöka antalet anläggningar.

Målet med detta arbete är att ta fram verktyg för att möjliggöra en kompetent utvärdering utifrån ett energieffektivt och miljönyttigt perspektiv, av nybyggda gårdsbaserad biogasanläggningar.

I detta examensarbete har data från nybyggda biogasanläggningar analyserats för att upptäcka möjliga misstag. Dessa misstag kan därigenom undvikas vid fortsätt expansion av biogasanläggningar.

Forskningen har skett inom ett SLF finanserad projekt ”Samverkan för lönsamhet och miljönytta i gårdsbaserad biogasproduktion”.

Data har insamlats och analyserats från anläggningar som redan är i drift, Högryd och Lövsta.

Detta examensarbete har funnit att den energianvändning och växthusgasutsläpp som investeras vid nybyggnation av biogasanläggning uppgår till 11-16 kWh/MWh och 2.65 – 3.65 kg CO_2-eq. per MWh av energi som produceras under anläggningens tekniska livslängd. Investeringen återbetalas med mer än 50 gånger under anläggningens tekniska livslängd.

Energikvoter beräknade individuellt för två av anläggningarna redogör för den tillgodogjorda energi produktionen.

Där framgår att 29 % av Högryds årliga energi produktion på 2 GWh kan tillvaratas i form av el och värme och därigenom till ekonomisk nytta. Vid Lövsta kan 62 % av dess produktion på 10 GWh tillvaratas som el och värme.

En större biogasanläggning har en högre elverkningsgrad, vilket ger en stor påverkan på den totala effektiviteten. Bidraget från värmeproduktion ska dock inte glömmas, då den ersatta energikällan är av särskild vikt. Att ersätta 120 MWh med olja och el kan få större påverkan än att ersätta 1.5 GWh med flis.

Executive summary

The thesis has found that the investment cost during the technical lifetime of the biogas plant at Lövsta is 11-16 kWh/MWh and 2.65 – 3.65 kg CO_2-eq. per MWh.

Companies that provide turn-key solutions for farm-based biogas plants may lack the competence to produce plants to the expectations of the purchaser.

It is possible to achieve a methane production/m^3 VS close to the ultimate potential value in a continuously stirred tank reactor (CSTR) biogas plant.

The average electrical efficiency of 100 kW CHP motor is approximately 30 %, while a 500 kW CHP motor can achieve 36 %.

It has been found that 29 % of Högryd's 2 GWh in energy production becomes usable electricity and heat; at Lövsta 62 % of its 10 GWh became usable electricity and heat. The usable electricity and heat is credited with avoided greenhouse gas emissions, thus each kWh of energy production from Högryd has a CO_2-eq reduction of 240 grams; at Lövsta each kWh has a reduction of 320 grams.

The energy ratio with a focus on primary energy factors showed that the replacement of 120 MWh of oil and electricity reduced the importation of fossil fuels more than the replacement of 1.5 GWh of wood chips.

Acknowledgement

This research was performed in conjunction with Karin Eliasson at Hushållningsällskapet who is the leader of a project to evaluate farm based biogas plants. Her help and access to data on the specific plants has been critical to the success of this research. I also thank my supervisor Cecilia Sundberg for her patience and help throughout my thesis work.

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Introduction

There is a scientific consensus that the anthropogenic greenhouse gas emissions have some impact on global warming. Many countries have decided to reduce their greenhouse gas emissions, calculated in terms of CO_2-equivalents, to minimize the chance of affecting the climate. The IEA has calculated a scenario to keep the increase in global mean temperature below 2 °C. It is projected that energy demand worldwide will double from 2009 until 2050. At the same time to achieve the IEA's goal the current fossil fuel portion of primary energy use must be reduced by 20 % compared to 2009 (IEA, 2013). This goal may be difficult to achieve, thus it is important to maximize the energy production from all forms of clean, safe, renewable energy technologies. This will likely include wind power, solar power and hydroelectric power as key electricity producing technologies. Nonetheless, biomass and waste, which can provide significant amounts of energy, both electricity and heat, will be important now and in the future. Currently biomass stands for 23 % of Sweden's primary energy use (Energimyndigheten, 2013). The majority of the biomass comes as byproducts from lumber and paper mills. A small part of the biomass energy production is biogas which comes from anaerobic digestion of substrates by microbes. Currently 1.5 TWh of biogas is produced in Sweden, but the research is conclusive; there is a potential of 8 TWh from manure and other agricultural residues (Linne, et al., 2008). However in 2012 only 47 GWh of energy was produced by farm based biogas plants (Energimyndigheten, 2013).

Thus farm-based biogas plants will represent a small drop compared to total energy demand in Sweden, but additional energy production from waste products such as manure is always of interest. While the concept of farm-based biogas plants is not new in Sweden achieving profitability is still difficult. In 2013, 31 plants were recognized as existing yet only 5 of the 31 plants had achieved break even (Bergh, 2013). This is true despite a subsidy that covered 30 % of the investment cost of the biogas plant. It would be positive to see an additional subsidy that rewards efficient biogas plants similar to the suggested methane reduction subsidy (Arnold, 2011).

To make this alternative more appealing it is important to show that the biogas plant will produce enough energy during its lifetime to motivate the additional investment.

If all of the inputs to a particular process are known and all of the outputs from by the process it is possible to assess the total impact of the process in reference to specified categories. The inputs will include the primary energy content of the steel, concrete, insulation, and electricity used. The outputs include the CO_2-equivalent released from the manufacture of the components listed. This methodology is commonly referred to as a life cycle inventory (LCI).

This thesis will perform a LCI of the investment (construction) phase of a farm-based biogas plant. Previous research had posited that the environmental impact of the investment phase only represents a small percentage of the total environmental impact during the lifetime of a biogas plant. However, the research has been done for a large scale biogas plant and the question is whether the results would differ in a farm-based biogas plant (Brogaard, 2013). This thesis will contribute life cycle inventory data from operating farm-based biogas plants.

Additionally, it is important to know what fossil-fuel primary energy reduction the biogas plant will result in. Since Sweden must import almost all of its fossil-fuels, this reduces dependence on foreign energy sources. The thesis calculates the energy ratios which express how efficiently the biogas is used and emphasize the realistic energy savings that the biogas plant can result in. Specifically the focus is on the production of biogas, electricity production and internal electricity use, and heat production and its utilization. It is imperative to maximize the energy potential of the substrates found at each individual farm. The amount of electricity and heat that is needed to run the biogas plant is of importance. The internal electricity use and the internal heat use are key factors in the calculations.

The thesis focuses on three farm based biogas plants in Sweden. Their annual energy production ranges from 2.3 GWh – 10 GWh and the ownership structure from a single farmer to a large organization. The plants also differ in their goals, but each exemplifies a potential benefit from investment in farm based biogas: nitrogen rich fertilizer (Hannson, et al., u.d.), biogas for vehicle fuel (VisitCleanTechWest, 2013), heating a crop dryer (Hushållningssällskapet, 2013), electricity production (Lantz, 2004), research in biogas, and heating buildings and stables (Granert, 2013).

The energy ratios are tools for determining if the production of energy from the biogas process is sufficiently energy efficient. Energy production is not the only parameter of interest in the biogas process, the quality of post-digestate can be even more important. But energy efficiency is an important parameter if a future large-scale expansion of farm-based biogas plants occurs. It is also relevant to have different metrics for measuring the impact of avoided electricity and heat production from conventional sources as explained below.

Goal

The aim of this report is to contribute to the technical evaluation of newly built farm-based biogas plants from an energy efficiency and greenhouse gas perspective; also to contribute useful data for a life cycle inventory on the construction phase with a focus on energy use and greenhouse gas emissions.

The primary objective of this thesis is to make higher quality data available for future research on farm-based biogas plants. The secondary objectives are:

- To share the experiences of the operators of farm-based biogas plants, helping future investors avoid problems, and showing to what extent operation and construction affect the energy balance of the plant.
- To calculate the energy use and greenhouse gas emissions invested in building a farm-based biogas plant.
- To analyze the biogas energy production and the internal electricity and heat use of a biogas plant and obtain data that enables the comparison of different farm-based biogas plants.
- To analyze the energy efficiency of individual plants and attempt to create appropriate tools for quantifying the results.
- To calculate the total primary energy savings and greenhouse gas emission reductions from the biogas plants

Approach of the work

The report consists of several sections, each focusing on one of the secondary objectives. The first two sections, the theory and the method, explain the relevant theory and present all of the calculations of the thesis. The remaining sections are presented with a short explanation

- Technical analysis of three farm-based biogas plants (Högryd, Lövsta, and Grinstad). Problems and experiences from plant operations are presented in addition to analysis and recommendations.
- Life cycle inventory of the construction phase (Lövsta). Energy use and greenhouse gas emissions were calculated.
- Energy (biogas, electricity and heat). The section presents relevant data from Lövsta and Högryd.
- Energy ratio (Lövsta and Högryd). Total energy efficiency of the biogas plant is calculated.
- Discussion
- Conclusion

Theory

Farm based biogas is produced through the process of anaerobic digestion of farm-sourced substrates. Anaerobic digestion is the term for the biologic decomposition of biodegradable materials in an oxygen free environment. Specifically carbohydrates, fats and proteins are converted through various microbial or biochemical processes into methane, carbon dioxide, hydrogen sulfide and ammonia. The lack of oxygen promotes the production of methane and carbon dioxide. The production of methane gas will depend on the amount of volatile solids in a given substrate, but also on the ability of the microbes to utilize the potential from different substrates. Furthermore, the composition of the substrates is important since fat will produce more methane than carbohydrates. The remaining mixture of substrates after the gas leaves the digestion chamber is known as post-digestate. The digestion process results in a lower dry matter content of the resulting post-digestate and organic nitrogen found in the substrates is partly converted to ammonia and ammonium which are easily accessible to crops (Jarvis & Schnürer, 2009). The nitrogen content can be increased by adding additional substrates, such as, chicken manure or straw bedding from cattle which contain additional nitrogen.

Substrates found at the farm scale can include liquid cattle or pig manure, solid chicken manure and straw bedding from cattle. Additional substrates can be added to maximize methane production, for example, flour and potatoes. The choice of substrate determines how the designed biogas process operates. Some substrates will require significant pre-treatment before the microbes will be capable of breaking down the substrate. This results in different electricity use depending on the plant. It has been found that a system with primarily liquid manure and some silage has the lowest electricity use at 2 kWh/ton substrate while the maximum in the case of a plant with significant food waste is 13 kWh/ton substrate. (Lantz, et al., 2009)

A mesophilic process was selected in all of the cases examined. This means that the substrates are pre-treated and mixed before being heated to approximately 38°C. The mixture is then pumped into the digestion chamber of the Continuously Stirred Tank Reactor (CSTR). The substrates are inhomogeneous and would naturally separate over time resulting in sedimentation at the bottom and a thick crust at the top. This would reduce available tank volume which in turn reduces possible gas production. Mixing of the digestion chamber is dimensioned to prevent sedimentation and the forming of a scum layer. The mixing requires electricity so it is important to properly size the system, an undersized or improperly installed system could lead to high electricity use with no benefit to be found. The goal is to find the optimum level of mixing to prevent a scum layer from forming but not over mixing and simply increasing the electricity costs (Christensson, et al., 2009).

Inside the digestion chamber microbes slowly break down the substrates producing methane, carbon dioxide and hydrogen sulfide. The methane and other gases rise to the top of the digestion chamber where they are removed via a pipe. A portion of the contents of the digestion chamber is also constantly removed to the post-digestion storage. Typically 55-80 % of the methane potential is achieved which leaves the possibility for post-digestion gas production. However, the biogas from the post-digestion storage may be technically difficult to handle due to lower content of methane gas; therefore before long term storage of post-digestate the temperature is lowered below 17°C to minimize the production of biogas. (Christensson, et al., 2009) The post-digestate is stored until the spring or autumn when it can be spread on the fields as fertilizer.

One of the products of the biogas process is hydrogen sulfide (H_2S) which can be corrosive in high quantities. Because of this there will often be a strict limit determined by the manufacturer of the CHP motor or set by the company purchasing biogas. Hydrogen sulfide reduction can be a part of the pre-treatment, digestion or post-treatment steps. During the pre-treatment step, liquid iron (III) chloride can be added to the substrates. It will react with the H_2S to form iron sulfide salt particles and is effective for reducing high levels of H_2S. (Krich, et al., 2005)

During the digestion step the mixing can be controlled to allow for a slight scum layer to form on the top of the digestate. This scum layer will provide a surface area for thiobacilli bacteria that can remove hydrogen sulfide. It is necessary to add oxygen to the digestion chamber just above the top of the digestate that the bacteria use. The H_2S is replaced with water and elemental sulfur left as a residue on the top of the digestate. (Krich, et al., 2005) Since the scum layer is a pre-cursor to a thick crust that should be avoided this method requires precision and fine tuning. A different idea is to install a net or wooden supports above the digestate to provide the surface area for the bacteria (Christensson, et al., 2009). This method was recommended because a scum layer could lead to an uncontrolled process or reduce production of biogas (Bengtsson, 2014).

Finally in the post-treatment step it is possible to remove H_2S from the biogas using an activated carbon filter. The gas pressure is increased using a fan before it passes through the activated carbon filter.

The conventional technique for spreading the digestate is using a tractor with a container for the post-digestate and an array of tubes connected to small knives that open up the soil (Figure 1). However, the concentration of nutrients is lower in the post-digestate than in NPK fertilizer, which results in a heavier tractor when the spreading of the digestate occurs. A heavier tractor can lead to damage of the soil, a problem which can be ameliorated through the use of a dispersal method using a hose to pump the post-digestate. This technology is based on a tractor attached by a hose to the post-digestate storage. A similar attachment as shown in Figure 1 can be used for the application of the post-digestate. The additional work involved is compensated for by the fact that the tractor is not carrying the container which can reduce the total weight from 50 tons to 16 tons. Conventional technology using a 12 meter axle can in soils susceptible to compaction result in 15-25 % lower crop yields. The alternative technology, a drag hose system, can result in as little as 0.7 -1.3 % lower crop yields. (Lantz, et al., 2009)

Figure 1: Conventional liquid manure applicator

Primary energy and CO_2-equivalent reduction

Primary energy is an energy found in nature that has not been subjected to any conversion or transformation processes. It is energy contained in raw fuels and other inputs to a system. It expresses the amount of energy resources required from source to final product. It is dependent on the efficiency of the transformation. For example, 1 kWh of electricity produced in condensing coal power plant will have a primary energy factor (PEF) of 2.61 (Gode, et al., 2011). On other hand, 1 kWh of heat from pellets has a PEF of 1.11. However, since wood pellets is a biomass fuel and Sweden must import the majority of its non-renewable fuels, only the primary energy from non-renewable fuels will be considered in this study (Energy, 2011). Thus, the PEF for wood pellets will therefore be considered to have a PEF of 0.11.

By producing electricity and heat in the CHP motor with biogas as a fuel, external electricity production and the local combustion of fuels to produce heat will be avoided.
The primary energy and CO_2-eq reduction will depend on the source of the replaced electricity and heat. First the possible sources of electricity are presented and followed by the sources of heat.

Depending upon how the electricity would otherwise have been produced, the PEF and CO_2-eq factor from the electricity production can be calculated. The choice of electricity mix will greatly influence the results. The following electricity mixes are possible to use:

- Swedish average electricity mix
- Nordic average electricity mix
- European average electricity mix
- Short term marginal electricity
- Long term marginal electricity

The PEF and CO_2-eq factors for each of the alternatives will depend on how the electricity mix is comprised. The first three are comprised of the average environmental impact from the production of electricity in Sweden, the Nordic countries and the European Union respectively. These three electricity mixes are based on the total production of electricity during a year in each area. The average electricity mix is a good way of analyzing the electricity use in the past.

For electricity use in the future the marginal production can be more accurate. Electricity production varies with demand and normally the energy source with the lowest marginal cost is used first. This is based on the cost of operation for the energy source including fuel costs but not including the initial investment. Therefore nuclear power or hydroelectric power will be the first choices. Electricity production with increasing marginal costs is used to meet electricity demand. The final produced kWh will correspond to the energy source with the highest marginal cost in an energy mix. (Gode, et al., 2009) This is the source that is replaced by the electricity from the CHP motor. Marginal electricity is expressed as either short-term margin or long-term margin. Short-term refers to the current electricity production mix while long-term refers to a future scenario where a different energy source produces the marginal electricity. Currently condensing coal power accurately models the short-term margin, while natural gas turbines may in the future model the long-term margin.

Still the question is if the PEF and CO_2-eq factor is calculated based on the average electricity mix or marginal electricity. There is no defined answer for the question and the choice will often depend on what the purpose of the study is. Since this study wishes to have a high primary energy and CO_2-eq reduction, short-term marginal electricity is used. This is reasonable considering the small volume of electricity produced, a time scale focused on current day conditions, and how important the production of biogas is.

In Table 1 the fossil energy percentage, the total CO_2-eq, and the primary energy factor for each mix is presented (Gode, et al., 2011) (Energy, 2011). Since, this thesis focuses non-renewable primary energy the PEF from the literature that include renewable energy creates problems. Therefore, the fossil energy content of each electricity mix is also presented. Fossil energy instead of non-renewable is chosen because of nuclear power which has a high PEF and distorts the results.

Table 1: Different electricity mixes

Electricity mix	**Fossil energy content (%)**	**CO_2-eq (g/kWh)**	**Primary Energy Factor**
Swedish average	3.68	36.4	2.1
Nordic average	14.80	97.4	1.74
European average	52	428.4	2.5
Long term margin	100	474	2.02
Short term margin	100	962.4	2.61

Table 2 shows the CO_2-eq factors and PEF for several fuels that can be used for heating.

Table 2: Global warming potential and PEF based on heat production fuel (Gode, et al., 2011)

Energy source	CO_2-eq g/kWh input energy	Primary Energy Factor
Oil (EO1)	295	1.11
Natural gas	248	1.09
Pellets	22	0.11
Nordic average electricity	98	1.74
Swedish electricity in heat pump[1]	15	0.69
Nordic electricity in heat pump[1]	32	0.57
European electricity in heat pump[1]	173	0.82
Short-term electricity in heat pump [1]	192	0.66
Long-term electricity in heat pump [1]	389	0.86

[1]The COP factor for the heat pump is 3, and the heat pump is dimensioned for 60 % of the maximum effect which covers 90 % of the annual energy need. The remaining heat is produced from electric resistance heating (Gode, et al., 2011).

These technologies will differ in the applications they can be utilized for. The combustion of fossil fuels can produce heat at high temperatures which may be necessary for a specific process at the farm in question. The heat pumps on the other hand deliver heated air or water and are usually used for heating of a building. The heat produced from the biogas CHP motor is approximately 85 °C and could be used for a crop dryer, which requires a temperature between 65-90°C (Andersson, 2013).

Energy and CO_2-equivalent ratio

The ratios are tools to determine if the production of energy from the biogas process is sufficiently energy efficient.

The first is the Energy ratio 1:1 where heat and electric energy have the same value. This ratio expresses the percentage of the total biogas energy used for a purpose separate from the biogas plant.

The second is the Energy ratio PEF which emphasizes the difference between electricity and heat. The energy ratio PEF expresses the replacement of non-renewable fuels. Since Sweden must import its non-renewable fuels the energy ratio PEF is a measure of the importation reduction.

The third is the Energy ratio exergy which expresses the amount of ideal work that was performed. Exergy refers to ideal reversible work. In theory the amount of work that can be converted into usable work and then returned to its original form (Gundersen, 2011). Electricity has an exergy factor of one whereas heat will have a lower exergy factor.

All of the three energy ratios are based on the lower heating value of the produced methane gas energy. They are dependent on the transformation losses in the engine, internal heat and electricity use, and net production of electricity and external heat use.

The electricity use is important at the individual biogas plants. To show the difference between electricity production and heat production for the ratios the three energy ratios are calculated once more with only the external heat use. This shows the particular importance of heat while showing that the remaining portion of the ratio is from electricity.

Furthermore a calculation of the energy ratio to ton substrate is calculated. This will express the total usable energy per ton of substrate. It will also show the replaced primary energy per ton substrate, which can be compared with a different plant.

Finally the CO_2-equivalent for the individual plants is calculated using the same methodology. The unit will be kg CO_2-eq/kWh which allows for easier calculation of the total CO_2-equivalent reduction. This in conjunction with the energy ratio PEF enables an effective communication of the results from an individual biogas plant.

Method

The study is based on data from individual plants. Data from Högryd was provided by Hushållningssällskapet, while data from Lövsta was provided by SLU. Field trips to the plants in Grinstad, Högryd and Lövsta have been undertaken to gain an idea of how the plants are built and operated. The data has been analyzed using Excel, with different calculations of the energetic qualities.

The theory of the biogas plants has been determined through interviews with those responsible for the various biogas plants. Supporting research is presented.

A calculation of all of the relevant parameters and key figures was done based on the data.

Technical analysis of three farm-based biogas plants

The technical analysis will categorize the problems into pre-treatment, digestion, and post-treatment. For the purpose of comparison it is helpful to separate the stages of a biogas process. The technical analysis also features a general overview of each biogas plant.

Energy and CO_2-eq costs for the construction phase

The energy and carbon dioxide equivalents invested in the construction of the biogas plant were calculated (1, 2)

$$Energy\ invested = \sum_{i}^{k} Mass\ of\ substrate_i * energy\ cost_i \qquad (1)$$

$$Carbon\ dioxide\ eq.invested = \sum_{i}^{k} Mass\ of\ substrate_i * CO_2\ eq._i \qquad (2)$$

where
i = the first substrate
k = the final substrate

The relevant values for the mass of materials were provided by the company that built the biogas plant (Petterson, 2013). Values that expressed the embodied energy and CO_2-eq. were found for each substrate listed. When possible a high value and a low value were found. The electricity invested in the construction of the biogas plant was estimated. Embodied energy and CO_2-eq. were calculated from this electricity assuming short-term marginal electricity as explained in the Energy and Greenhouse gas emission reduction section. From the weight of the substrates an estimate of the transportation greenhouse gas emissions was calculated.

The ratio between the primary energy and CO_2 invested and the energy production during the technical lifetime of the plant was also calculated. The annual biogas energy is the estimated biogas energy amount the facility should produce.

$$Energy\ investment\ cost = \frac{Energy\ invested}{Annual\ biogas\ energy * Technical\ lifetime} \quad (3)$$

$$Carbon\ dioxide\ investment\ cost = \frac{Carbon\ dioxide\ invested}{Annual\ biogas\ energy * Technical\ lifetime} \quad (4)$$

Energy

The focus is on the production of biogas, electricity production and internal electricity use, and heat production and its utilization.

Biogas

The focus is on maximizing the production of methane from the given substrates. Based on the "Handbook of Substrates" by Svenskt Gastekniskt Center AB it is possible to determine an ultimate methane gas production for the given substrates (Carlsson & Uldal, 2009). The values from SGC were determined from batch digestion for a period of 50-60 days which can result in higher values than are possible if the substrates in the biogas plant are present during a shorter time. A second calculation was performed using values from digestion in a CSTR with a hydraulic retention time closer to 30 days.

The methane gas potential is calculated from the weight of the substrates.

$$Theoretical\ methane\ production = \sum_{i}^{k} Mass\ of\ substrate_i * \%\ TS_i * VS\%\ of\ TS_i * \frac{Nm^3 CH_4}{ton\ VS}_i \quad (5)$$

However, this assumes that the weight of the substrates is known. This was not the case for the first plant. There the volume of substrates added is known and the ratio between the different substrates.

$$Theoretical\ methane\ production = Volume\ of\ susbtrates * \frac{Nm^3 CH_4}{m^3\ substrate} \quad (6)$$

$$\frac{Nm^3CH_4}{m^3\ substrate} = \sum_{i}^{k} \%\ of\ total\ volume_i *\ density_i * \%\ TS_i * VS\%\ of\ TS_i * \frac{Nm^3CH_4}{ton\ VS}_i \quad (7)$$

$$\%\ of\ total\ volume = \frac{Volume\ of\ substrate}{Total\ volume\ of\ mixture} \quad (8)$$

$$Total\ volume\ of\ mixture = \sum_{i}^{k} \frac{Mass\ of\ substrate_i}{Density_i} \quad (9)$$

The annual expected weight of the substrates was known which meant the total volume could be calculated (9). Then each substrates fraction of the total volume was determined (8). Multiplying this fraction by the density and then substituting in to equation 5 resulted in equation 7. This was then used in equation 6 to calculate the theoretical methane production.

The ratio between the measured methane gas production and the theoretical based on the values from SGC was calculated as shown in equation 10.

$$SGC\ ratio = \frac{measured\ methane\ gas\ production}{SGC\ theoretical\ methane\ gas\ production} \quad (10)$$

The ratio between measured methane gas production and theoretical, approximates the portion of the total methane potential in the substrates accessed during the digestion.

Electricity

The biogas production expressed in Nm^3 was known, from it the lower heating value of biogas energy production was calculated (11).

$$Biogas\ energy = Nm^3 biogas * \%\ of\ methane * 9.81\ kWh \quad (11)$$

The average electrical efficiency of the CHP motor was calculated based on the measured production of electricity and the calculated biogas energy production (12).

$$n_{el} = \frac{Electricity\ production}{Biogas\ energy} \quad (12)$$

If electricity measurements did not exist for the whole measurement period, the average electrical efficiency was used to calculate the total electricity production.

The internal electricity use was measured and the net electricity production was found by subtraction the internal electricity use from the electricity production.

The ratio between internal electricity use and total production was calculated (13).

$$Internal\ electricity\ ratio = \frac{Internal\ electricity\ use}{Electricity\ production} \quad (13)$$

The ratio between internal electricity use and biogas energy production was calculated (14).

$$Electricity\ use\ as\ percentage\ of\ gas = \frac{Internal\ electricity\ use}{Biogas\ energy} \quad 14$$

Last, the ratio between internal electricity use and the weight of the substrates was calculated (15).

$$\frac{Inernal\ electricity\ use}{ton\ substrate} = \frac{Internal\ electricity\ use}{Total\ volume\ of\ substrates * density} \quad 15$$

Heat

The heat production was not measured instead it was calculated based on the heat efficiency of the CHP motor which is dependent on the rated electrical output of the CHP motor (Lantz, 2012).

The available heat energy was calculated by subtracting the internal heat use from the total heat production.

At Högryd the internal heat use was not known; instead this value was calculated based on a theoretical model of the energy demand of the digestion chamber.

$$Internal\ heat\ use = Mass * C_p * \Delta T * Q_{loss} - \frac{1}{2} * Mass * C_p * \Delta T \quad 16$$

mass - total annual mass of substrates
C_p *- specific heat capacity of the mixture*
ΔT *- difference between 38 °C and the average temperature in the region*
Q_{loss} *– additional factor which represents the heat loss from the digestion chamber* (Bacenetti, et al., 2013)
½ - a heat exchanger exists which recovers half of the energy needed to heat the substrates (Lantz, 2004)

The ratio between internal heat use and total biogas energy was calculated (17).

$$Internal\ heat\ use\ as\ percentage\ of\ gas = \frac{Internal\ heat\ use}{Biogas\ energy} \quad 17$$

Not all of the heat available can be used at each plant. The heat utilization, which is the ratio between external heat use and available heat energy, was calculated (18).

$$Heat\ utilization = \frac{External\ heat\ use}{Available\ heat\ energy} \quad 18$$

Energy and CO_2-equivalent ratios

The energy and CO_2 ratios were calculated using data of external heat use, net electricity production and total bioenergy production.

The first was the Energy ratio 1:1 where heat and electric energy have the same value. This is a physical allocation where the used electricity and heat was summed and divided by the total methane gas energy (19).

$$Energy\ ratio\ 1{:}1 = \frac{Net\ electricity + External\ heat\ use}{Biogas\ energy} \tag{19}$$

The second ratio was the Energy ratio PEF which was based on the same values of electricity and heat as Equation 19, but included primary energy factors (20).

$$Energy\ ratio\ PEF = \frac{Net\ electricity * PEF + External\ heat\ use * PEF}{Biogas\ energy} \tag{20}$$

The third ratio was the Energy ratio exergy (21).

$$Energy\ ratio\ exergy = \frac{Net\ electricity * 1 + External\ heat\ use * Exergy\ factor}{Biogas\ energy} \tag{21}$$

Electricity has an exergy factor of 1 while the exergy factor for heat was calculated (22).

$$Exergy\ factor = 1 - \frac{T_0}{T} \tag{22}$$

Where T_0 is temperature of surrounding air
T is temperature of heat source
(Gundersen, 2011)

$$CO_2eq.ratio = \frac{Net\ electricity * CO_2eq.factor + External\ heat\ use * CO_2eq.factor}{Biogas\ energy} \tag{23}$$

The energy and CO_2-eq ratios were calculated a second time, with only the external heat use. The energy ratio heat 1:1 was calculated as shown (24). The procedure was the same for the three other ratios.

$$Energy\ ratio\ heat\ 1{:}1 = \frac{External\ heat\ use}{Biogas\ energy} \tag{24}$$

Finally, the energy ratios were calculated a third time, including the net electricity and external heat use but dividing by the total substrate mass (25).

$$Energy\ production\ ratio\ 1{:}1 = \frac{Net\ electricity + External\ heat\ use}{Total\ \ substrate\ mass} \tag{25}$$

The same substitution of denominator was performed for the three other ratios.

The total primary energy and CO_2-equivalent reduction was calculated using the results of Equations 20 and 24 multiplied by the biogas energy.

$$Primary\ energy\ reduction = Energy\ ratio\ PEF * Biogas\ energy \qquad 26$$

$$CO_2 eq. reduction = CO_2 eq. ratio * Biogas\ energy \qquad 27$$

The ratio between the primary energy savings at Lövsta for a given MWh and the primary energy investment cost at Lövsta was calculated.

$$Primary\ energy\ repayment = \frac{Energy\ ratio\ PEF * 1\ MWh}{Energy\ investment\ cost} \qquad 28$$

$$Carbon\ dioxide\ repayment = \frac{CO_2\ eq. ratio * 1\ MWh}{Carbon\ dioxide\ investment\ cost} \qquad 29$$

Results

Technical analysis of three farm-based biogas plants

Högryd

Högryd located in Varberg municipality, is an organic milk farm with approximately 260 milking cows. The owner invested in a biogas facility motivated by two main considerations. The first is the possibility of producing a nitrogen rich ecologically certified fertilizer. Also, the plant is designed to produce enough heat that a crop dryer can be utilized. The additional heat and electricity that would be produced was important for the overall profitability of the plant but was not seen as the key product. The planned production of electricity was 700 MWh annually with production starting in 2011.

Figure 2: Högryd including digestion chamber and machine building

The biogas plant consists of an 1150 m^3 digestion chamber, a pre-mixing tank, a small gas storage, and a building containing pumps, heat exchangers, boiler, and a 99 kW_e motor (Figure 2). The substrates consist of cattle manure, chicken manure and cattle straw bedding. A mixer wagon, a machine used to mix the solid substrates, is used on the chicken manure and straw bedding. The resulting mixture is mixed into the cattle manure using propeller fans installed in the pre-mixing tank.

The slurry is then pumped through a heat exchanger which raises the temperature to the 38 °C temperature of the digestion chamber. The contents of the chamber are mixed using external pumps which remove a portion of the slurry, heat it and pump it back into the chamber (Figure 3). A top-mounted propeller mixer is also employed to ensure an adequate mixing of the contents. The produced biogas is removed from the top of the chamber and pumped to the gas storage. The post-digestate is pumped from the tank and through the heat exchanger that preheats the incoming slurry. A heat pump is then used to lower the temperature of the post-digestate below 20°C. The post-digestate is stored in covered post-digestate storages until application to the field using a tractor with a suitable attachment for pumping the post-digestate onto the field. A portion of the post-digestate is pumped back to the pre-mixing tank due to a need for additional liquid in the process. The produced biogas is combusted in the 99 kW_e motor and the resulting electricity and heat are used to the degree possible. There is often an overproduction of heat that must be removed using fans; this requires electricity and is one of the problems existing with the plant. The usable heat is delivered to a local district heating system, while excess heat is cooled away. The cooling is not shown in the process diagram.

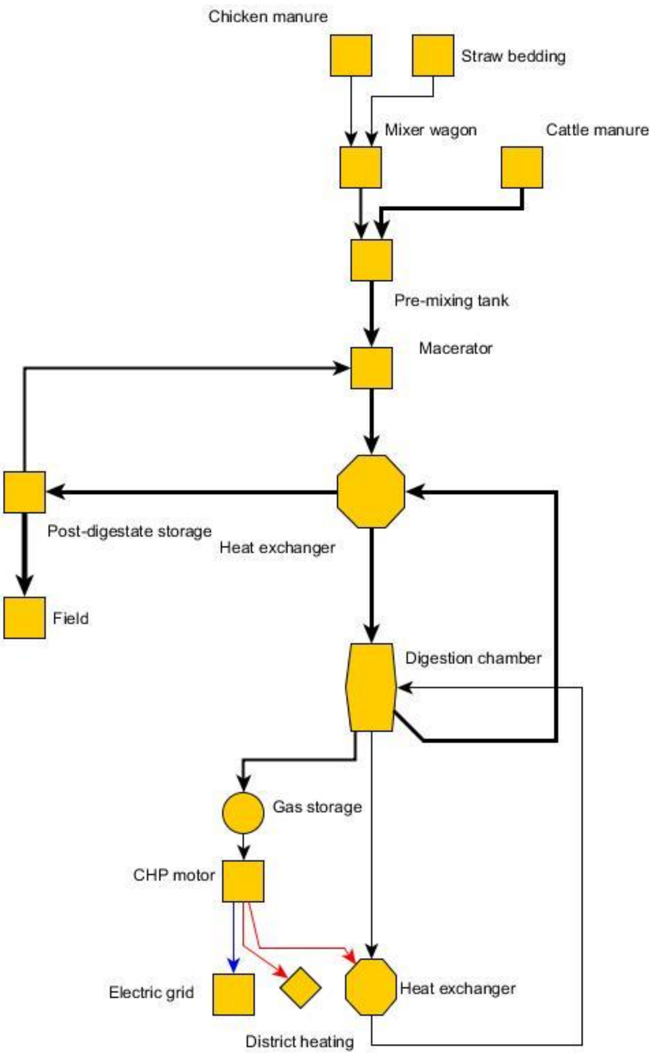

Figure 3: Process diagram for Högryd, where the different thicknesses represent the different volumes at various parts of the process.

Table 3: Problems occuring at Högryd

Pre-treatment	Digestion	Post-treatment
Solid substrates in large pieces	Insufficient mixing of digestate	Excess heat
Insufficient mixing in tank	High electricity use	

Högryd has faced several problems during its early years, most of which stem from the same source: the high concentration of solid substrates. (Table 3) Pumps have clogged due to the substrates. The digestion chamber developed the dual problems of sedimentation at the bottom and a thick crust at the top. Both processes reduce the active volume of the chamber. The biggest problem has been that the electricity consumption of the plant has been significantly higher than what was promised by the company that built the biogas plant. Before additional steps were taken, the electricity consumption had climbed to 163 MWh instead of the promised 60 MWh per year.

The solution to the problems has been increasing the mixing capacity of the pre-mixing tank and the digestion chamber. Additionally a large mixer wagon has been added for the solid substrates before the pre-mixing tank. (Figure 4) The need for new equipment is expensive and difficult to incorporate during operation. For example, the new top mounted propeller that has been installed required the digestion chamber to be opened and drained which meant that production was halted for approximately five weeks. The excess heat from the CHP unit must be cooled away which requires additional electricity and was not anticipated.

Figure 4: Högryd's mixer wagon

The plan is that after the additional investments in the form of mixers, the electricity use will be approximately 120 MWh. This however, does not include the use of electricity in the feed mixer or the pump that transports a portion of water in the post-digestate to the pre-mixing tank. The additional electricity use has been calculated to 54.5 kWh daily or 19.9 MWh annually. The original projected electricity consumption was set at 60 MWh annually; therefore there will be costs incurred from the additional 80 MWh of internal use electricity that the farmer must provide. The firm that was contracted to build the biogas plant signed a contract guaranteeing that the plant would fulfill certain conditions that have not been achieved. The owner of Högryd has the right to sue for damages incurred due to the failure of the company to deliver the promised results.

Lövsta

Lövsta is a farm in Uppland run by SLU and features 300 cattle,130 sows and 2000 pigs raised for slaughter that are part of various research projects. The plant has a planned energy production of 10 GWh/year and started production in 2012. In Figure 5 the back of the biogas plant is shown including the digestion chamber and the liquid manure storage tank, also referred to as the pre-mixing tank.

Figure 5: Lövsta biogas plant featuring pre-mixing tank (right) and digestion chamber

The biogas plant consists of a 3600 m^3 digestion chamber. The liquid manure is pumped from the cattle and pig yards to a 100 m^3 storage tank. The liquid manure is pumped continuously using a pump with a capacity of 6 m^3/h. There is a daily flow of 60-80 m^3 of liquid into the digestion chamber and a corresponding flow out of the chamber; these two flows pass through a heat exchanger that increases the temperature of the incoming substrate by 10 °C. A 50 m^3 feed mixer is used to reduce the particle size of the solid substrates. The solid substrates such as potatoes, flour and silage are added every half hour and pumped through a transport screw and mixer into the digestion chamber. At this point a portion of the digestate is mixed with the solid substrates so the mixture can be pumped into the digestion chamber. Every day on average 6 tons of flour residues from the grain mill in Uppsala and 1 ton of potatoes are added. (Figure 6)

The chamber is mixed using a top mounted propeller mixer with two sets of blades, one at the bottom and another near the top. The production of biogas, approximately 200-250 m^3/h with an average methane content of 52%, at Lövsta is used in a combined heat and power unit delivered by Jenbacher. The unit delivers a maximum of 527 kW electric power and 540 kW heat power. The gas is removed from the digestion chamber and pumped to the 20 m^3 gas storage. A fan is used to raise the pressure of the gas before it passes through a carbon filter. Afterwards the gas is sent to the engine which has 29 liters of volume. The heat production is led into the local district heating grid at Lövsta. To reduce the presence of hydrogen sulfide one ton of iron oxide is added to the digestion chamber every tenth day. Air is also added above the surface of the digestate within the digestion chamber.

Figure 6: Lövsta solid substrates, flour and potatoes

Lövsta has a total of 17000 m^3 of post-digestate storage. Additional storage of 5000 m^3 is located approximately 10 kilometers away. There is an annual production of 22-23000 m^3 of post-digestate. The post-digestate is spread on the fields at Lövsta that consist of approximately 1500 hectares. Spreading is done using the conventional technique of a slurry tanker with dribble bar. A plan to pump the digestate through a pipeline to the intermediate storage tanks near the fields in question will be implemented to reduce the need for transportation to the field. In Figure 7 the process diagram for Lövsta is presented.

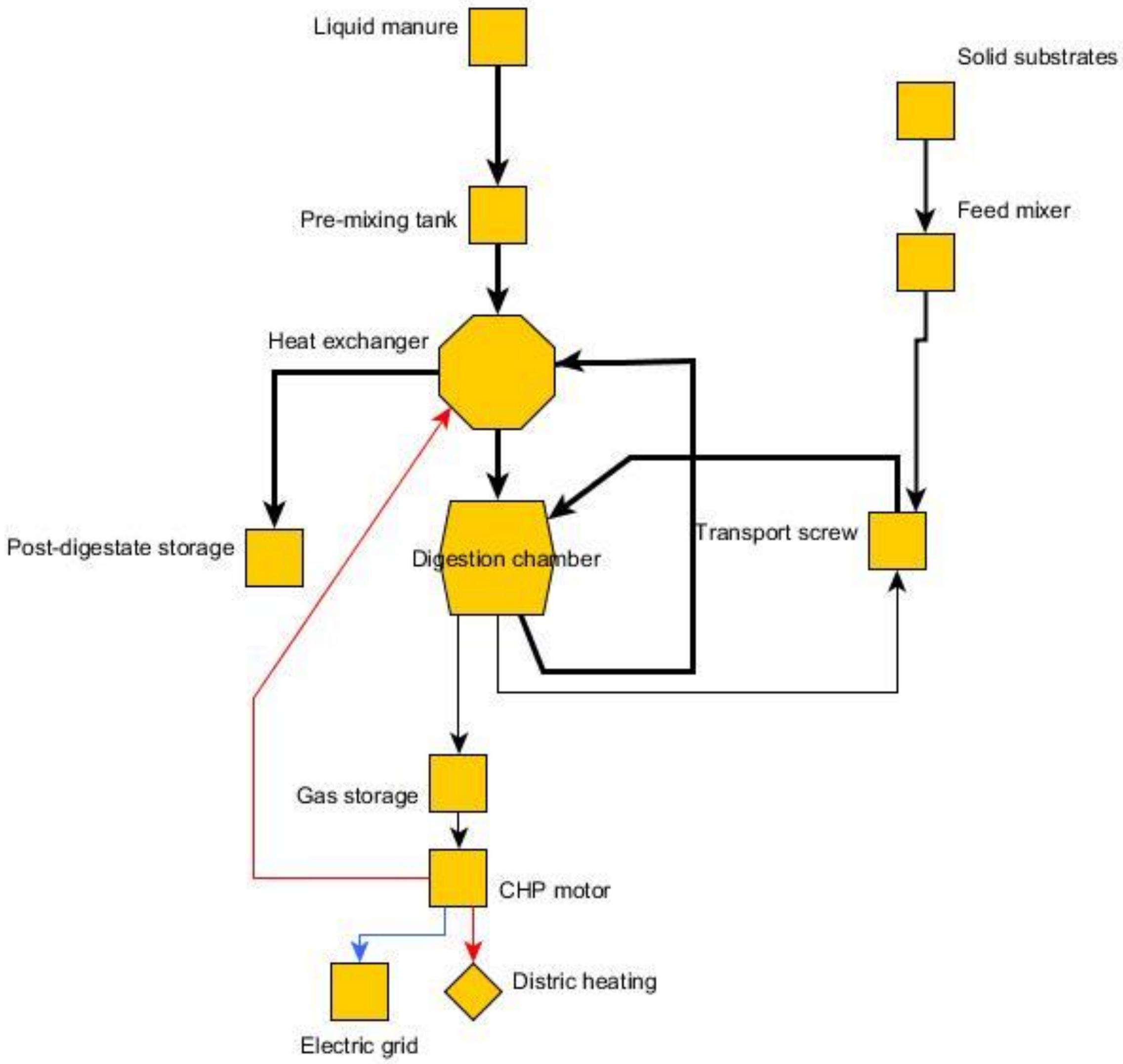

Figure 7: Process diagram for Lövsta

The plant manager anticipated that problems would occur during the first period of operation. The use of silage with long individual pieces led to jammed pumps which could be easily dealt with. During the beginning months the generators stopped several times due to various malfunctions which inevitably led to flaring of the produced gas. Perhaps the biggest problem resulted from condensate in the gas lines which needed to be adjusted. (Table 4) However, the problems that occurred were deemed acceptable during the start-up of the plant and understandable considering the heavy frost. While some problems existed they were not significant enough to create major difficulties.

Table 4: Problems occurring at Lövsta

Pre-treatment	Digestion	Post-treatment
Clogged pumps		Condensate in gas pipeline

Grinstad

The biogas plant is owned by six farmers whose substrates are used in the production of biogas. The previous investment subsidy that existed only granted funding up to a certain ceiling. This promoted the creation of four smaller biogas facilities, one of which is co-owned by the six farmers (Benjaminsson & Benjaminsson, 2013). The size of the plant has been identified as a key problem because the technology was not originally designed for small-scale plants. The interviewed farmer felt that cost considerations may have led to selection of sub-optimal equipment for the plant (Hilmer, 2013). The plant has an annual planned production of 3.45 GWh and started production in 2012 (VisitCleanTechWest, 2013). The produced biogas is sent via low-pressure gas pipeline to an upgrading station. The digestion chamber is shown in Figure 8.

Figure 8: Grinstad's digestion chamber

The plant features a 2000 m^3 digestion chamber with a conventional mixer at the bottom of the chamber, in conjunction with a pump which is used to pump the top most layers to the bottom. The plant uses liquid cattle and pig manure, as well as slaughterhouse residues. The substrates are transported by truck to the biogas facility and stored in a 500 m^3 pre-mixing tank. The same truck is then used to transport the post-digestate, which is stored in another 500 m^3 tank, back to the farms (Figure 9). Hygenisation occurs at the slaughterhouse before transport. The substrates are mixed in the pre-mixing tank before proceeding to the macerator. The resulting digestate is then heated using a heat exchanger before being pumped into the digestion chamber.

Figure 9: Transport tanker carrying liquid manure

The anaerobic digestion is based on a mesophilic process. (Figure 10) The digestion chamber is heated externally. The digestion chamber is mixed by a submerged propeller mixer near the bottom of the chamber. Additionally, another propeller mixer moves the top layer of the digestate down to the bottom. A portion of the substrate is pumped out of the digestion chamber and heated to process temperature before being returned to the digestion chamber. The gas is removed from the chamber and cleaned before the temperature is lowered. The gas is then pumped into a low-pressure gas pipeline that connects the plant to the upgrading station. The digestate is pumped into the post-digestate storage. To reduce the production of methane during storage the temperature is lowered to less than 20 °C. A heat pump is used to reduce the temperature and to pre-heat the incoming substrates.

Table 5: Major problems encountered during production start-up

Pre-treatment	**Digestion**	**Post-treatment**
Clogged pumps	High content of hydrogen sulfide	Condensate in gas pipeline
No drain in equipment room	Top-bottom circulation failed	Heat exchanger in post-digestate storage tank failed

A number of problems have been encountered during the start-up of Grinstad (Table 5). In the pre-treatment process, pumps and pipes have clogged, mainly due to the low speed the manure passes through the pipes. When these clogs were cleared out it became apparent that there was no drain in the equipment room, meaning the room needed to be cleaned by mop every time there was a clog. A drain has since been added to the equipment room.

Within the digestion chamber there have been problems with a high content of hydrogen sulfide, which has been combatted by adding iron (III) chloride and oxygen to the digestion chamber. There have also been difficulties with the top-bottom circulation due to poor positioning of the nozzle at the top of the chamber. At some point additional mixing will likely be required, because the current system does not appear able to handle all of the substrate planned at maximum production.

In the post-treatment process, there were problems with condensate in the low pressure gas pipeline. This was fixed by adding a possibility for the condensed water to drain. The original plan had been to heat the digestion chamber using heat from the post-digestate storage tank through a heat exchanger. However, after a month the heat exchanger failed, and was replaced with a heat-pump.

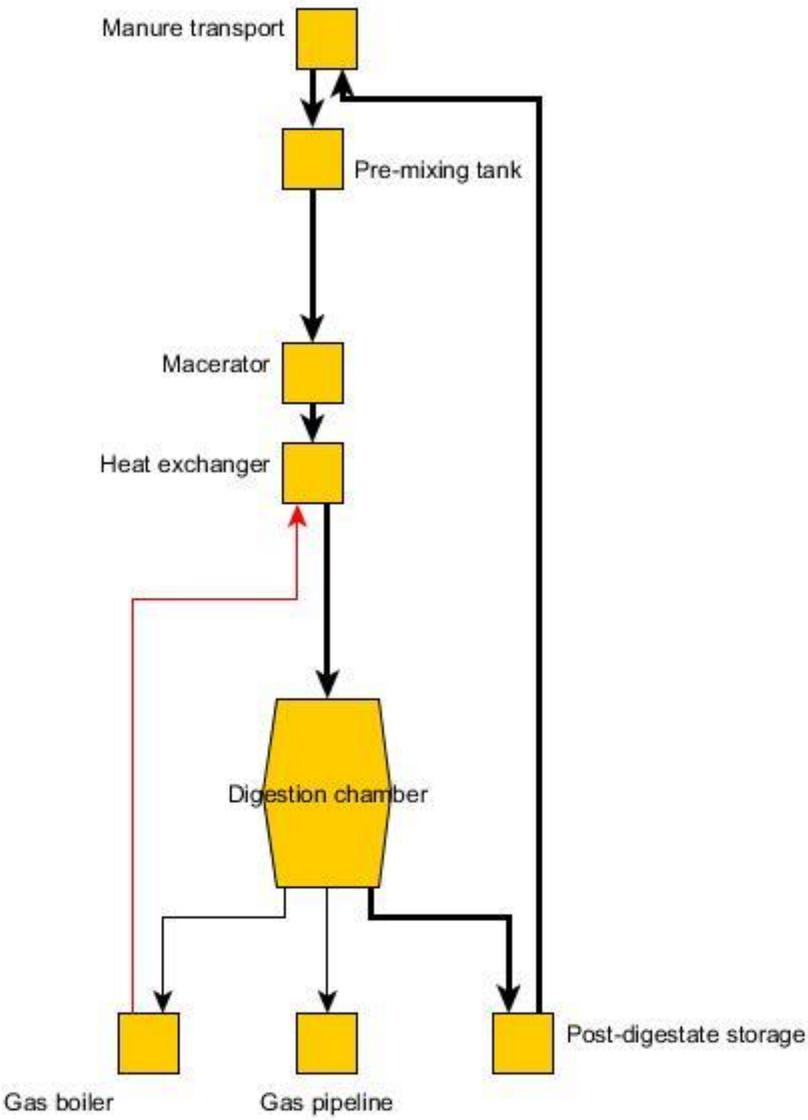

Figure 10: Process diagram for Grinstad

In addition to the above problems encountered during production start-up, some other significant problems have challenged the successful establishment of the plant. The farmers believed that they had selected a "turn-key" biogas plant, expecting the venture to be similar to a previous investment in a wind turbine. The anaerobic digestion of substrates with a focus on producing biogas and nutrient rich digestate is a complicated process, however, and unlike a wind turbine that can transfer ownership when the supplier has proved that it is working reliably, a biogas plant is a sensitive process that needs an extended period of optimization before a steady state can be achieved, and will always need to be carefully monitored, even in the best of cases. In contrast to the previously purchased wind turbine, the farmers have found the level of time and effort required to establish the biogas plant to far exceed their “turn-key” expectations.

During construction, difficulties arose that required the farmers (and the contractor) to invest significant additional time and money. Some of these difficulties were related to the unproven down-scaling of the contractor’s technology, but others were more related to planning and communication. For example, the farmer had agreed to supply the foundation for the plant, but disagreement in the building process meant that machinery needed to be rented several times instead of only once.

Despite the above problems, there are positive aspects that should be noted in this plant as well: The plant has been certified, with the boiler of the plant acting as the flare. Instead of directly flaring the biogas that is of low quality or cannot be transported, excess gas is used for heating the digestion chamber. Additionally, the post-digestate produced by the plant has been found to be easier to handle than the original substrates. Specifically, less stirring is needed in the post-digestate storages compared to the previous liquid manure lagoons, and it is easier to pump the post-digestate as well. Currently the farmers utilize a conventional tractor-drawn manure spreader for application of the post-digestate, but discussion is underway to invest in a drag hose system to reduce the damage from soil compaction.

Recommendations

One of the main reasons for an investment in a biogas plant is to produce a good quality fertilizer, which may require additional nitrogen sources such as chicken manure. It is imperative that process requirements of the additional solid substrates be respected. When planning the biogas plant, the size of mixers and macerators should be chosen depending on the substrates. It may be wise to choose a higher level than what has been calculated as being required. The additional initial investment is better than incurring greater costs at a later date if additional mixing capacity must be added. The additional substrates result in more complicated preparation steps which have a higher investment cost and use more electricity. It may be wise to perform calculations taking into account the higher electricity use that will exist in a plant with greater dry matter content. It may be interesting to check if the benefit accrued from the additional substrates will cover the increased costs inherent in the choice.

It appears that there is less pressure that a biogas facility should operate smoothly when the owner has a lower financial stake in the facility. If possible a form of risk sharing would be recommended to allow for individual farms to make the investment without needing to take the same financial risk. In biogas plants where the gas is upgraded it is common for an energy company to own a portion of the biogas facility. (Benjaminsson & Benjaminsson, 2013)

Energy and CO_2-eq costs for the construction phase

By calculating the amount of various materials existing in the Lövsta biogas plant and determining the energy and environmental impact of building it, it is possible to find values for the initial investment in a biogas plant. The company that built the Lövsta plant gave help in determining the amounts of various materials present (Petterson, 2013).

Table 6: Amount of common materials with their energy and global warming potential for Lövsta biogas plant

Material	Total weight (tons)	Primary energy cost (MWh/ton)	Global warming potential cost (kg CO_2/ton)
Concrete	200	0.26[i]	130[a]
		0.694[b]	110[b]
Steel	180	6.78[a]	1 770[a]
		6.00[c]	1 350[c]
		8.75[d]	1 750[d]
Stainless steel	56	16[a]	6 150[a]
		24.6[d]	6 330[d]
		13.8	3 810[e]
Fiberglass insulation	2.5	7.78[a]	1 530[a]

[a] (Hammond & Jones, 2008)

[b] (NRMCA, 2012)

[c] (Tata, 2014)

[d] (Jernkontoret, 2013)

[e] (ISSF, 2010)

The most frequently used reference was an inventory of carbon and energy created by Professor Geof Hammond and Craig Jones. The inventory often presents many different values which can be chosen from. Other references include a handbook on the environmental impact of steel that directly correlates energy cost with environmental cost specifying 16-20 MJ/kg CO_2 for steel and 12-14 MJ/kg CO_2 for stainless steel. The third set of references include a fact sheet on concrete by the NRMCA, values given by Tata for their steel, and values by the ISSF for stainless steel. Electricity use during the construction of the plant was estimated at less than 10 MWh which represents 26.1 MWh of primary energy and 9 624 kg of CO_2. An additional 11 840 kg of CO_2 represents the calculated transportation emissions for the materials.

Table 7: Energy and environmental cost of materials used for construction of Lövsta biogas plant

	Energy cost (MWh)	**Environmental cost (tons of CO2)**
(Hammond & Jones, 2008)	2240	729
(Jernkontoret, 2013),b	3175	723
b, c, e	2075	510

[b] (NRMCA, 2012)

[c] (Tata, 2014)

[d] (Jernkontoret, 2013)

[e] (ISSF, 2010)

Based on the data presented in Table 6, the data presented in Table 7 was calculated. The first calculation was performed using the same data source for all materials (Hammond & Jones, 2008). The second calculation used two references (Jernkontoret, 2013) (NRMCA, 2012). The final calculation used three references (NRMCA, 2012) (Tata, 2014) (ISSF, 2010).

The calculations show that for a biogas plant with a 3600 m^3 digestion chamber producing 10 GWh of energy annually and 23000 tons of post-digestate, there will be an investment of 2075– 3175 MWh and 510 – 730 tons of carbon dioxide. A technical lifetime of the plant at 20 years is assumed, which is reasonable for the digestion chamber. The CHP motor and additional machines have a 5 year technical lifetime, which meant that this analysis assumes they have been purchased 4 times (Hartman, 2006). Based on this the investment cost during the technical lifetime of the plant is 11-16 kWh/MWh and 2.65 – 3.65 kg CO_2-eq. per MWh (Equation 3, Equation 4).

This analysis is focused on the investment phase of the biogas plant only parameter not present in this calculation is the energy use and environmental impact of the construction machines. This is a difficult parameter to measure after the construction has already occurred and was not determined even in more complicated studies of biogas plants (Brogaard, 2013) .The values should not be seen as conclusive; instead it should be seen as an approximation.

Energy

Biogas

One of the questions that this analysis focused on was the efficiency of the biogas process. The goal was to determine which percentage of the maximum methane yield the various plants achieved.

Högryd

The biogas production at Högryd is based on three substrates: an annual estimated use of 11000 tons of liquid cattle manure, 630 tons cattle straw bedding, and 750 tons of chicken manure (Eliasson, 2013). The density of liquid cattle manure is by convention 1 ton/m^3, while the density of straw bed cattle and chicken manure was found in a publication by Jordbruksverket (Jordbruksverket, 2010). As part of an ongoing project the total solids (TS) of the substrates were determined and are listed in Table 8 (Hushållningssällskapet, 2013). The volatile solids (VS) value is calculated from the ratio between TS and VS values according to the Handbook of Substrates (Carlsson & Uldal, 2009).

The values for methane yield/ton VS for each substrate were taken from the Handbook of Substrates. However, these values were determined by experiments focusing on the maximum methane potential from the substrate. For a more realistic comparison with the measured results it is possible to use values from a mesophilic process in a Continuously Stirred Tank Reactor (CSTR). A feasibility study for anaerobic digestion in Oregon presented a breakdown of expected results for the digestion of liquid cattle manure with an average value of 174 m^3 CH_4 per ton VS (Oregon, 2009). In a report by Hushållningssällskapet the maximum methane yield from straw bedding is displayed in a graph relating methane yield to days of digestion. Based on Högryd's hydraulic retention time (HRT) of 32 days a methane yield of 200 m^3 CH_4 per ton VS could be determined from the graph (Eliasson, 2010). The characteristics used in calculation of the factors are displayed in Table 8.

Table 8: Characteristics of the substrates

Substrate	Mass (ton)	Density (ton/m³)	Total Solids[a]	% VS of TS[b]	SGC Yield $\frac{Nm^3CH_4}{ton\ VS}$	CSTR yield $\frac{Nm^3CH_4}{ton\ VS}$
Liquid cattle manure	11000	1	8%	80%	213	174[c]
Straw bed cattle	630	0.5[d]	27%	80%	250	200[e]
Straw bed chicken	750	0.5[d]	67%	76%	247	200[d]

[a] (Hushållningssällskapet, 2013)

[b] (Carlsson & Uldal, 2009)

[c] (Oregon, 2009)

[d] (Jordbruksverket, 2010)

[e] (Eliasson, 2010)

Table 9: Theoretical methane production factor

	(Nm^3 CH_4/m^3 substrate)
SGC yield	20.21
CSTR yield	16.43

In Table 10 the results of the calculation of ultimate SGC methane gas production are compared with the measured values. The SGC and CSTR yields were calculated assuming the ratio of substrates is constant.

Table 10: Theoretical SGC and CSTR methane gas production May 2012- April 2013

	Volume of substrates added (m³)	**Measured methane gas production (m³)**	**Ultimate SGC methane gas production (m³)**	**Ratio**	**Theoretical CSTR methane gas production (m³)**	**Ratio**
May	1829	29233	36957	79	30 052	97
June	965	13916	19499	71	15 856	88
July	1002	17220	20246	85	16 464	105
August	998	17548	20166	87	16 398	107
September	1036	18491	20933	88	17 023	109
October	1227	15708	24793	63	20 161	78
November	967	9911	19539	51	15 889	62
December	1064	11920	21499	55	17 483	68
January	829	15103	16751	90	13 621	111
February	795	16346	16064	102	13 063	125
March	889	16063	17963	89	14 607	110
April	1029	20577	20792	99	16 908	122
Total	**12630**	**202036**	**255202**	**80**	**207 525**	**99**

The ratio to SGC in Table 10 shows that on an annual basis the biogas plant produced almost 80 % of the theoretical SGC methane gas. Additionally, the ratio to CSTR has an average of 99 % which points towards an effective process. Since the ratio to SGC was 80 % additional methane gas potential could perhaps be accessed if the HRT was increased. In specifically the ratio to CSTR variations are obvious between the different months. The most noticeable difference is during October – December which had a lower production compared to the months before and after. Between December and January the production jumps from 68 % in one month to 111 % in the next. It is possible that this change reflects a variation in the monthly substrate composition.

Table 11: Results after additional mixer added July 2013- Sep 2013

	Volume of substrates added (m^3)	**Measured methane gas production (m^3)**	**Theoretical SGC methane gas production (m^3)**	**Ratio**	**Theoretical CSTR methane gas production (m^3)**	**Ratio**
July	1 099	19 195	22 206	86	18 058	106
August	1 284	21 055	25 944	81	21 098	100
September	1 025	15 595	20 711	75	16 842	93

There have been changes to the biogas facility that will most likely change the production. As previously explained in the technical analysis, Högryd had problems with mixing inside the digestion chamber. An additional, top mounted propeller mixer was installed between May and June. Table 11 shows the results from the most recent data available, July – September 2013. The ratios to SGC and CSTR for the first two months is either at or above the previous average which may be the result of a more successful process. The ratio is lower than during the previous year with a slight decreasing trend.

Lövsta

The same analysis was performed for the Lövsta biogas plant. However a key difference was that the substrates were given in terms of mass which meant that the calculations were simplified since the density was not needed. Instead of calculating a methane yield based on a combined value of the substrates, the methane yield for each substrate was calculated and the results summed up.

In Table 12 the five substrates and the data needed to calculate the SGC theoretical methane gas production are presented. Equation 5 is used where “l” = liquid pork manure and “k” = silage.

Table 12: Substrate characteristics Lövsta

Substrate	**Mass (ton)**	**Total Solids**	**% VS of TS**	**SGC Yield**[ii] $\frac{Nm^3 CH_4}{ton\ VS}$
Liquid pork manure	2 181	6.2%	77%	268
Liquid cattle manure	8 591	6.2%	77%	213
Straw bed cattle	211	27%	80%	250
Flour	699	88%	95%	390
Silage	1710	23%	92%	300

[a] (Carlsson & Uldal, 2009)

In Table 13 the measured methane gas production is compared to the SGC theoretical methane gas production.

Table 13: Comparison between measured and theoretical SCG methane gas production

	Measured methane gas production (m^3)	Theoretical SGC methane gas production (m^3)	Ratio
February	56855	61141	93
March	68967	65677	105
April	66989	64113	104
May	73089	72541	101
June	63344	55567	114
July	80618	68788	117
August	65434	75282	87
Total	**475296**	**463109**	**103**

The average ratio between measured and theoretical SGC is 103 %. This is an excellent result for Lövsta, which in turn means that there exists a degree of uncertainty as to why the result is higher than the theoretical SGC methane production. Most likely, since Lövsta has a HRT of approximately 50 days the biogas production is higher than achieved in experimental case. Future analysis at Lövsta should examine the substrates and their biogas potential to determine more accurate values for the theoretical methane potential. Nonetheless, the initial results from Lövsta are encouraging.

Electricity

Högryd

In Table 14 the biogas energy production, electricity production and electrical efficiency are presented. The electrical efficiency varies from 28 -33 %. While values for the energy can be calculated from May 2012 to April 2013, relevant measurements of electricity were only available during the months listed in the table.

Table 14: Electricity production compared to energy production during selected months

Month	Biogas energy production (kWh)	Electricity production (kWh)	Electrical efficiency (%)
April	173857	52136	30.0
June	136517	44756	32.8
July	168925	49611	29.4
August	172145	49821	28.9
September	181392	50930	28.1
January	148164	43674	29.5
February	160350	49592	30.9
Average			**29.9**

The average electrical efficiency is used with the total biogas energy production to calculate the total electricity production (Table 15). Since the internal electricity use in the biogas process is known the net production of electricity can be calculated.

Table 15: Electricity production data and results in one year at Högryd

Energy in gas (MWh)	1 981 983	Calculated from measurements
Average electrical efficiency	29.9 %	Calculated from measurements
Electricity production (MWh)	593 406	Calculated from measured data
Internal electricity use (MWh)	139 600	Measured at Högryd
Net production electricity (MWh)	453 806	
Internal electricity ratio	24%	
Percentage of gas	7%	
Internal electricity use/ton substrate	12.28 kWh	

As shown in Table 15, the net production of electricity in one year is just under 454 MWh. The internal electricity ratio is 24 % which is problematic because the profit from electricity sale is lower than expected. The electricity use/ton substrate is 12.28 kWh which is at the upper range for biogas facilities (Lantz, et al., 2009).

Lövsta

Table 16: Electricity production compared to energy production during selected months

Month	Energy production (kWh)	Electricity production (kWh)	Electrical efficiency (%)
February	557 750	218 100	39.1
March	676 570	245 200	36.2
April	657 170	228 500	34.8
May	717 000	306 300	42.7
June	621 400	157 100	25.3
July	790 860	261 700	33.1
August	641 910	257 600	40.1
Average			**35.9**

The data that exists for Lövsta is presented in the Table 16. It is clear that the motor is more efficient than at Högryd. This is logical considering the far greater energy production at Lövsta in comparison to Högryd; also the electrical efficiency of the motor increases proportionally with the size of the motor (Lantz, 2012). The increased electrical efficiency will lead to a more efficient use of the produced biogas.

Table 17: Electricity production data and results in one year at Lövsta

Energy in gas (MWh)	4 663 000	Measured
Electricity production (MWh)	1 674 500	Measured
Internal electricity use (MWh)	134 700	Measured at Lövsta
Net production electricity (MWh)	1 539 800	Calculated
Internal electricity ratio	8%	
Electricity use as percentage of gas	3%	
Internal electricity use/ton substrate	10.06 kWh	

The internal electricity use was significantly less for Lövsta which leads to benefits when compared to Högryd. Also, electricity/ton substrate is at a reasonable level considering the high methane potential from the substrate.

Heat

Depending on the system, heat can be one of the most profitable products of a biogas plant. However, it can also be seen as a byproduct of the electricity production. In Sweden, the economy of a plant is typically dependent on an efficient utilization of produced heat and steps to minimize internal heat use. As not all of the heat will be used it is important to differentiate between produced heat and heat used for a purpose separate from the biogas plant. How the heat is used may have an important role in the environmental benefit of a typical biogas plant.

Högryd

The data from Högryd was used to highlight the net production of heat after the internal demands of the biogas process are satisfied. In Table 18 we can see the data that was used to calculate internal heat use according to Equation 16 and the result of the calculation. Further down in Table 18 we see the total biogas energy and the heat efficiency of the CHP motor. The heat efficiency is dependent on the size of the CHP motor (Lantz, 2012). It expresses the portion of the biogas energy that is converted to heat. The true efficiency of the motor varies with time, maintenance and load but for the purpose of a theoretical value the assumption is reasonable.

Table 18: Heat production data and results in one year at Högryd

Total volume of substrate (m^3)	12 630	Measured at Högryd
Specific heat capacity of substrate (MJ/ton*°C)	3.80	Calculated from measurements
Density of substrate (ton/m^3)	0.985	Calculated from assumptions
ΔT (°C)	31	Average temperature is 7°C
Q_{loss}	1.2	Assumed (Bacenetti, et al., 2013)
Internal heat use (kWh)	383 976	Calculated
Produced methane gas (m^3)	181 459	Measured at Högryd
Total biogas energy (kWh)	1 981 983	Calculated from measurements
Heat efficiency	50 %	Assumed(Lantz, 2012)
Heat production	990 992	
Net production of heat (kWh)	607 016	Calculated
Internal heat use as percentage of gas	19 %	
External heat use (kWh)	125 000	
Heat utilization	21 %	

All told the result of the calculation was an internal heat demand of just under 384 MWh which results in a net heat production of 506 MWh. The internal heat use as a percentage of gas was calculated according to Equation 17. The heat utilization ratio was calculated according to Equation 18

Before building the biogas plant Högryd had a crop dryer that had an annual consumption of 11 m3 of oil. This heat source was replaced by heat from the CHP unit. The main farm house was previously heated by waste heat from the milk production. This was sufficient until the outside temperature dropped below 7°C. The remaining heat was provided by electric radiators. A rough estimate results in an electrical energy demand of 15 000 kWh. A cubic meter of oil contains approximately 10 000 kWh of energy. This means that for Högryd approximately 125 MWh of heat will be used every year.

Lövsta

The measurements at Lövsta included the internal heat use within the biogas process and the external heat use which replaced biomass in the form of dried sawdust.

Table 19: Heat usage at Lövsta

Month	Energy production (kWh)	Internal heat use (kWh)	External heat use(kWh)
February	558 000	45 200	191 300
March	676 500	49 000	227 800
April	657 000	40 100	218 300
May	717 000	23 200	256 300
June	621 000	9 900	116 300
July	791 000	1 600	136 100
August	642 000	8 600	192 600
Total	4 662 500	177 700	1 338 700

The heat efficiency of the CHP motor at Lövsta was 40 %. While the electrical efficiency increases with increasing size, the heat efficiency decreases with increasing size. The same ratios were calculated using Equations 17 and 18.

Table 20: Results of heat use at Lövsta

Total biogas energy production (kWh)	4 662 500
Total heat production (kWh)	1 865 000
Internal heat use (kWh)	177 700
Internal heat use as percentage of gas	3.80 %
Net heat production (kWh)	1 687 300
External heat use	1 338 700
Heat utilization	79 %

Energy ratio

The energy ratio is an attempt to create a metric that can be used to compare separate biogas plants and their processes on the basis of the energy efficiency of the process. All values are expressed as a ratio between the energy used for useful work and energy found in the produced biogas. The values are thus dependent on the electrical efficiency of the CHP motor and how the produced electricity and heat are used. Useful work does not include electricity and heat needed for the biogas process itself. The expected result of the calculation was that Lövsta would be more efficient than Högryd. Much of this is due to the significant size difference between the two plants. A larger plant benefits from a more efficient CHP motor, wider economic margins and the ability to use conventional techniques.

Table 21 presents the values of energy used in the calculations which have been calculated and presented in earlier sections, while Table 1 and Table 2 present the primary energy and CO_2-equivalent factors pertinent to the calculations.

Table 21: Data on energy used to calculate energy ratios

	Högryd	**Lövsta**
Total energy production (kWh)	1 981 983	4 662 500
Net electricity production (kWh)	453 806	1 539 800
External used heat (kWh)	125 000	1 338 700
Total mass of substrates (tons)	11 367	13 392

It is important for the calculations performed to note that Högryd used its heat to replace 110 MWh of oil and 15 MWh of electricity. Lövsta used all of its heat to replace biomass.

The exergy factor expresses the efficiency at which the energy can be converted into useful work. The exergy factor is based on the temperature of the heat from the CHP motor, 85 °C, assuming an average outside temperature of 6 °C (CIBSE, 2012). The exergy factor is calculated using Equation 25 to 0.22. The exergy factor for electricity is by definition 1.

Electricity and heat

Equations 19, 20, and 21 were used to calculate the following ratios based on the data given in Table 1, Table 2, and Table 21.

As previously explained in the theory, the 1:1 ratio values heat energy and electrical energy the same and expresses what portion of energy in the biogas was used for some beneficial purpose. Primary energy ratio is based on the calculation of the replacement of non-renewable primary energy due to the heat and electricity production. Exergy ratio expresses the exergy replacement possible from the production of heat and electricity in the given situation.

Table 22: Energy ratio based on CHP

	1:1 Ratio	**Primary Energy**	**Exergy**
Högryd	0.29	0.68	0.25
Lövsta	0.62	0.89	0.39

There is a big difference between Högryd and Lövsta. The purpose of this calculation is not to prove a particular plant is better than another. Instead it should highlight the overall efficiency of the plants and give an understanding of what remains to be achieved.

Högryd had a 1:1 ratio of 0.29. This means that 29 % of the total energy in the biogas was converted to externally used heat and electricity. The annual energy production from Högryd is approximately 2 GWh; therefore, 29 % of this energy could be used for a purpose separate from the biogas plant. The primary energy ratio, 0.68, means 68 % of the 2 GWh is saved in terms of primary energy savings. Since the primary energy is based on non-renewable fuels, which Sweden does not possess, Högryd has achieved a reduction in the import of non-renewable fuels equivalent to 68 % of 2 GWh.

The results from Lövsta, which has projected energy production of 10 GWh per year, were also positive. Sixty-two percent of the energy production will be realized in externally used heat and electricity. The biogas plant will annually reduce the Swedish import of non-renewable fuels by 89 % of 10 GWH or 8.9 GWh of primary energy. The exergy analysis shows that 39 % of the 10 GWh is saved, for a total of 3.9 GWh of exergy.

Heat

In Table 22 there is a big difference between the 1:1 ratio of Högryd and Lövsta, yet a substantially smaller difference between the primary energy ratios. Table 23 shows the energy ratios but calculated only using the externally used heat, to show the difference between various sources of heat.

Table 23: Energy ratio for heat energy

	1:1 Ratio	Primary Energy	Exergy
Högryd	0.06	0.08	0.02
Lövsta	0.29	0.03	0.06

At Högryd 6 % of the 2 GWh is used as heat, which corresponds to 8 % of 2 GWh in terms of primary energy. However, at Lövsta 29 % of its 10 GWh is used as heat, which only corresponds to 3 % in terms of primary energy. In real terms Högryd's 120 MWh of heat is equivalent to 160 MWh of primary energy savings. Lövsta's 2.9 GWh of heat is equivalent to 300 MWh of primary energy savings. The replacement of a small amount of oil and electricity may be better than replacing a 10 times greater amount of biomass, at least in terms of primary energy.

Net energy

It is also possible to calculate the net energy benefit from an average ton of substrate from each of the plants. In Table 24 it is clear that Lövsta has a higher result from a given substrate which is explained by high energy potential, low internal energy use, and high external energy use. It should be noted that approximately 25 % of the methane potential comes from flour and silage which most likely have alternative uses unlike liquid cattle manure.

Table 24: Net energy benefit (kWh) /ton substrate

	1:1 Ratio	Primary Energy	Exergy
Högryd	51	118	43
Lövsta	215	311	137

Högryd will produce 51 kWh of usable energy from each ton of average substrates. Since it has annual use of approximately 11 000 tons of substrates, this gives approximately 561 MWh of usable energy. This can be used to make a quick calculation of the impact of introducing additional substrates. If primary energy is considered each ton of substrates results in a savings of 118 kWh.

Lövsta will produce 215 kWh from each ton of substrate, which corresponds to 311 kWh of primary energy.

CO_2-equivalent reduction ratio

Table 25: CO_2-equivalent reduction ratios

	Electricity and heat (g/kWh)	Heat (g/kWh)	Net energy (kg/ton)
Högryd	240	230	42.5
Lövsta	320	70	112.9

Table 25 presents the CO_2-equivalent reduction ratios for Högryd and Lövsta. These were calculated based on the previously stated assumption that produced electricity and heat replaces other energy sources. The benefit of this analysis is that it shows the results from the climate perspective. Also in conjunction with the energy ratio PEF the estimated primary energy and CO_2-equivalent reduction can be calculated.

Primary energy and CO_2-equivalent reduction

Equations 26 and 27 were used to calculate the total primary energy and CO_2-equivalent reductions. For Lövsta the known results were used, which was from a production of only seven months. A calculation assuming the planned energy production of 10 GWh is inaccurate because the ratio of external electricity and heat use may change during the remaining months. That being said, the calculation was performed and should be seen as only a guideline of what the true result will be.

Table 26: Primary energy and CO_2-equivalent reduction

	Primary energy (GWh)	CO_2-equivalent (tons)
Högryd	1.35	484
Lövsta	4.17	1511
Lövsta (one year)	8.94	3242

Analysis

Why did Lövsta have a better result than Högryd? As can be seen by comparing Table 22 and Table 23, Lövsta had a greater external heat use than Högryd but the primary energy of heat use was lower. Nonetheless the total primary energy ratio seen in Table 22 is better for Lövsta, which is due to its larger share of usable electricity. In total 33 % of biogas energy could be used as electricity at Lövsta, while only 23 % at Högryd. This big difference is the sole reason that Lövsta achieved a better primary energy ratio than Högryd. The same is true for the CO_2-equivalent ratios, as seen in Table 25 the CO_2-equivalent ratio based on heat was 3 times greater than Lövsta. Nonetheless, the total CO_2-equivalent ratio was larger for Lövsta.

The difference in usable electricity comes from two things: electrical efficiency of the CHP motor and internal electricity use of the biogas process. Högryd's CHP motor had an efficiency of 30 % and an internal electricity use of 6.7 %. Lövsta's CHP motor had an efficiency of 36 % and an internal electricity use of 2.9 %. The difference between the two CHP motors is significant enough that Lövsta would invariably have the better energy ratio.

An additional factor that differed between Högryd and Lövsta can be seen in the internal electricity use per ton substrate. This ratio which was presented in Table 15 and Table 17, 12.28 kWh/ton substrate and 10.06 kWh, is important. The biogas plant at Högryd required almost 25 % more electricity for an average ton substrate yet as seen in Table 24, Lövsta had an energy ratio PEF almost three times greater for each ton of substrate. The point of this is that Högryd has achieved a good result considering its circumstances.

Discussion

The energy ratios determined in this thesis clearly show the total energy efficiency of the individual biogas plants and opens for a comparison of biogas plants in the future. The analysis of the importance of the construction of the biogas plant has shown that the energy and CO_2 investment will be a mere fraction of the total production. The gathered experiences from plant operators would suggest that choosing properly sized mixing equipment is crucial for long-term success. The study of the theoretical methane production showed both plants had a high measured to theoretical ratio considering their differing circumstances. As a side note, the analysis has shown that in terms of biogas plants, increasing size will result in higher electrical efficiency of the CHP motor.

The importance of the energy ratio is that at Högryd and Lövsta the exact ratio of electricity and heat that actually served some purpose is now known. Previously it was stated that in 2012 47 GWh of biogas energy was produced (Energimyndigheten, 2013). But, the energy ratio shows that not all of this production can be used. More importantly the energy ratio could be used to compare different biogas plants. The goal should be to achieve the highest primary energy savings and the greatest CO_2-equvalent reduction. But, as was seen in the previous chapter, 120 MWh of heat replacing oil and electricity from Högryd had greater primary energy content than 1.5 GWh of heat replacing wood chips at Lövsta. The question is if our society should promote the greater primary energy savings or greater physical energy savings. Also it is likely that 1.5 GWh of wood chips would be cost more than 120 MWh of oil and electricity.

Next, the energy and CO_2-equivalents that were invested in the Lövsta biogas plant resulted in an investment cost of 11-16 kWh and 2.65 – 3.65 kg CO_2-eq. per MWh produced during a 10 year life time. The energy ratio PEF and CO_2-eq. ratio for Lövsta was 0.89 and 320 respectively. Based on this the primary energy and CO_2-equivalent repayment ratio can be calculated to 56-81 and 88 -121, respectively (Equation 28 and Equation 29). The investment in a biogas plant at Lövsta was repaid almost immediately; hopefully the same is true economically. Just recently an LCA of an industrial scale biogas plant concluded that the investment phase would represent 4-5 % of the total impact during the biogas plant's lifetime (Brogaard, 2013). This thesis has a similar result but from a different perspective.

From the technical analysis two important points should be mentioned. First, do not skimp on the mixing capacity. It is better to have a mixing system that is bigger and stronger than expected. The point of the mixing system to avoid scum and crust formation, the extra capacity can be necessary during unexpected problems that may otherwise lead to a crust that cannot be removed. The second point to mention is that when choosing a company to plan and build a biogas plant, it is important to verify that the company has the competence to deal with the chosen substrates and size of the plant.

A recent study of farm based biogas plants found that for the majority of owners the biogas facility was unprofitable. Also, the time spent on the biogas facility varied from 5 – 175 hours/month with an average of 42 hours/month. (Bergh, 2013) While it is true that many of the plants were recently built and had not reached stable operation it is important to understand that the initial work can be significant. Considering the many other responsibilities that a farmer holds, it is wise to have a realistic understanding of the time and cost of a biogas plant before the investment decision.

Biogas production is dependent on the amount of substrates but it is interesting to see the differences among various plants. Of particular interest is the difference in the ratio of actual biogas production compared to theoretical SGC production. Högryd had an average ratio that was less than 80 % while the result from Lövsta was closer to 103 %. While Högryd still has some potential to achieve, Lövsta has surpassed the expected results.

There was also a significant difference in the internal electricity and heat use between the two plants. While Högryd used 12.28 kWh of internal electricity use /ton of substrates and Lövsta used 10.05 kWh, the internal electricity use was 7 % of biogas energy at Högryd while 3 % at Lövsta. Yet, the values are comparable to the range between 2-13 kWh/ ton mentioned in the theory (Lantz, 2012). At Högryd the internal heat use 19% of the biogas energy, while at Lövsta it was 3.80 %. This remarkably large difference could be the result of a miscalculation. But as it is Lövsta cannot use all of its heat, so the additional heat use will not affect the total energy ratio. Instead the excess heat may be a burden which makes it less important to accurately measure the usage of heat. This was different at Grinstad where the gas was delivered to a low pressure gas grid. There the internal heat use should be kept as low as possible to reduce the use of gas for heating.

A side benefit of the calculation of the average electrical efficiency for the different plants is it has shown that a larger plant has a higher electrical efficiency. An increase in electricity production will result in a higher overall efficiency according to the energy ratio PEF. There may be other parameters that will scale with increasing size, such as, the net energy benefit as seen in Table 24. There can be an argument for biogas production in larger scale plants, for example at a multi farm level. Increasing the size will result in a higher electrical efficiency and possibly other positive effects. But, there will be negatives to consider, like transportation distance. Also, if the plant is no longer located near an individual farm the opportunity to use the heat for purposes at the individual farm will be lost which would reduce the overall efficiency of the biogas plant. It cannot be stated categorically that larger biogas plants will have a higher efficiency, but there are reasons to consider larger biogas plants.

Increasing the overall efficiency of farm-based biogas plant is one of underlying themes within this thesis. But as was seen in the energy ratios listed in Table 22 the efficiency will vary greatly depending on how the electricity and heat are valued. The choice of energy ratio 1:1, PEF or exergy will determine the choices that will be made. If the goal is to maximize the energy ratio 1:1 than the path presented at Lövsta may be most logical. However, if the goal is to maximize the energy ratio PEF a situation similar to Högryd may occur where 120 MWh of heat is valued higher than 1.5 GWh of heat. The efficiency of the biogas plant will always depend on the criteria that are used to evaluate it.

It should be mentioned again that the interpretation of the primary energy content of fuels as solely non-renewable primary energy is different than the choice in my source for primary energy content (Gode, et al., 2011). Certainly, including renewable primary energy has its purpose but it would change the interpretation of the results if oil and biomass had the same primary energy content. The primary energy factors listed in this thesis were cradle-to-factory. Thus they did not include the electricity that would have been lost in the power lines or the efficiency of the wood chip and oil boilers. Therefore, the true answers may differ but the hope is that the values shown in Table 1 and

Table 2 could be used when calculating the results for other plants.

Future Work

The ratio between measured and theoretical SGC methane gas production was 103 %. This suggests that the values that the SGC has calculated can be improved. It would be interesting in a future study to re-evaluate the methane potential for the substrates used at Lövsta. Perhaps then it will be possible to say if additional methane potential exists.

It may also be helpful to calculate the energy ratios for more of the farm-based biogas plants currently existing in Sweden and worldwide. Then the biogas plants with the highest energy ratio could be studied in closer detail to see if the success could replicated at different plants.

Conclusion

The aim of the thesis has been fulfilled; this thesis has evaluated the operation of three farm-based biogas plants including the efficiency of two of the plants. It has proven that the two main plants that have been analyzed are effective at producing biogas of good quality that can be used in a CHP motor to provide electricity and heat. They can and will become more efficient in the future as a result of the ability to compare the results between different plants. The ratios that are presented in this thesis allow for an effective comparison of the efficiency of different plants with a focus on the energy content, primary energy content, exergy content or CO_2-equivalent replaced. The need to focus on the mixing inside the digestion chamber has been demonstrated. It has been proven that the primary energy and CO_2-equivalent investment cost of the biogas plant is repaid more than fifty-fold. Both plants achieved a high ratio between measured methane gas production and theoretical. Internal electricity use per ton of substrate was within the normal values for other biogas plants. The replacement of 120 MWh of oil and electricity is better than replacing 1.5 GWh of heat from wood chips.

This thesis has shown that increasing the numbers of farm-based biogas plants in Sweden will reduce the import of non-renewable fuels. Reduction of CO_2-equivalents goes hand in hand with non-renewable energy import reductions. Bigger farm-based biogas plants are able to achieve higher electrical efficiency of the CHP motor which in turn leads to a better overall efficiency. The thesis has provided quality data for future research into the field of farm-based biogas plants. It is the hope that research in the future can give a more accurate picture of the varied benefits to society that farm-based biogas plants bring.

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