2021

Increased biogas production in the municipality of Borås

A STUDY OF ORGANIC MATERIALS THAT CAN BE UTILIZED FOR ANAEROBIC DIGESTION IN THE SURROUNDINGS OF BORÅS

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ACKNOWLEDGEMENTS

In the process of researching and writing this master thesis, I had great support from several people.

Firstly, I want to thank Robert Kjellstrand and Camilla Ölander at “Borås Energi & Miljö” for the opportunity to do this master thesis. Additionally, for their willingness to answer all my questions, both about the facility at Sobacken and other questions related to anaerobic digestion.

I also want to thank my supervisor at Chalmers, Britt-Marie Wilén, especially for the help with administrative issues and in the writing process. Moreover, I want to thank my brother Erik Axelsson who has offered several hours to correct the language in this report, during my writing process.

Even the company “VH Biogas” in Vårgårda should receive an enormous thanks for all the experience they have given me during my two summers working at their facility. But also, for the data about transports they gave me during the writing process of this thesis. I even want to thank all who set aside time for my interviews.

/Jakob Axelsson

SUMMARY

South of Borås, at Sobacken, biogas is produced from out-sorted food waste. Organic material is degraded in an anaerobic digestion process which results in biogas. The plant is owned by "Borås Energi & Miljö", a company owned by the municipality of Borås. During 2021 a reconstruction is finished, and some new technologies are launched in the process. There are especially two important changes that are the provocation for this report. Firstly, there is a new technology for handling solid waste materials that ease the handling of large quantities. Secondly, the old digester tank is now used as a post-digester, which leads to a duplication of the digestion volume.

To fill the extra digestion volume, that the reconstruction results in, a study of organic waste materials in the surroundings is made. The study begins with theory about the most common organic wastes in the region. These are cattle manure, pig manure, horse manure, chicken manure and food waste from industries. From the theory, biogas potentials for the different types of materials are collected. The biogas potentials are then used for calculations of the sustainable transport distances considering energy balance and economical balance.

In the beginning of the analysis, all the farms holding cattle, pigs, horses, or chickens, in the surroundings of Sobacken, are mapped out. Together with the calculations of sustainable transport distances, the map stands as ground for the advocation of using manure for biogas production at the facility. Horse manure and food waste from industries can be collected in large quantities due to the good possibilities of handling solid wastes, with the new technology. Manure slurry from cattle and pigs can replace some need for water in the process but mainly fill the remaining need of extra organic material in the digestion process. Digestion of several different materials together do often result in extra biogas yield compared with digestion of partial materials. Together, the analyzed organic materials have the possibility to fill the extra digestion volume and increase the biogas production at the facility.

SAMMANFATTNING

Söder om Borås, på Sobacken, produceras biogas av utsorterat matavfall. Organiskt material bryts ned i en syrefri rötningsprocess som resulterar i biogas. Anläggningen ägs av det kommunala bolaget ”Borås Energi & Miljö”. Under 2021 färdigställs en ombyggnation av anläggningen som medför att ny teknik ska tas i bruk. Det är två viktiga förändringar av anläggningen som ligger till grund för denna rapport. En av dem är lanseringen av en ny förbehandlingsanläggning för fast avfall som förenklar hantering av stora kvantiteter. Den andra är att den gamla rötkammaren nu ska användas som efterrötkammare, vilket leder till en fördubblad rötningsvolym.

För att fylla den extra rötningsvolym som ombyggnationen leder till är en studie över organiska avfall i närområdet gjord. Studien börjar med ett teoriavsnitt om de vanligaste organiska avfallen i regionen. Avfallen som studeras är nötgödsel, svingödsel, hästgödsel, fjäderfägödsel och avfall från livsmedelsindustrin. Från teorin är biogaspotentialen hämtad för de olika avfallen. Biogaspotentialerna är sen använda för att beräkna respektive avfalls hållbara transportavstånd, med avseende på energiförbrukning och ekonomisk lönsamhet.

I början av analyskapitlet är alla gårdar i närområdet som håller nötkreatur, svin, hästar eller höns kartlagda. Tillsammans med beräkningen av transportavstånd används kartläggningen som grund för att förorda biogasproduktion från gödsel på anläggningen. Hästgödsel och avfall från livsmedelsindustrin kan mottagas i stora kvantiteter i den nya förbehandlings-anläggningen. Flytgödsel från nötkreatur och svin kan ersätta ett visst behov av vatten i förbehandlingsanläggningen men främst fylla behovet av en större volym organiskt material till rötningsprocessen. Samrötning av flera olika material resulterar ofta i högre biogasutbyte jämfört med rötning av ensidiga material. De analyserade materialen har tillsammans möjligheten att fylla den extra rötningsvolymen och öka biogasproduktionen på anläggningen.

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INTRODUCTION

Rising atmospheric greenhouse-gas levels are a common target of new research and development projects. There are several ways of attacking this enormous and worldwide issue. Much of the focus is on decreasing the carbon dioxide (CO_2) emissions to lower the greenhouse effect. But there are also more problems to solve in case of saving our planet from global warming. One such challenge is to reduce the methane (CH_4) emissions, as methane in the atmosphere creates a disproportionately strong greenhouse effect. The average lifetime of methane in the atmosphere is 12.4 years and the CO_2-equivalents calculated in a 20-years perspective for methane is 86 $kgCO_2/kgCH_4$ (IPCC, 2013, p.731).

At the end of its lifetime, the methane in the atmosphere is transformed into carbon dioxide, which still contributes to global warming negatively. Due to this, it is important that the source of the methane is renewable to make sure that the circulatory system is closed. Fossil methane which can be found in natural gas is therefore negatively affecting the environment by only adding new greenhouse gases to the ecosystem. Methane produced in the near time from for example household waste is already part of the ecosystem.

However, it is still a waste of energy to let methane into the atmosphere without using its inherent energy potential. When combusting methane, energy and even carbon dioxide are released. But even unburned methane will eventually be transformed into carbon dioxide after a decade in the atmosphere. Utilizing the energy in the methane and emitting carbon dioxide, instead of the 86 times worse methane, is the better option. The natural cycle for methane is illustrated in Figure 1.

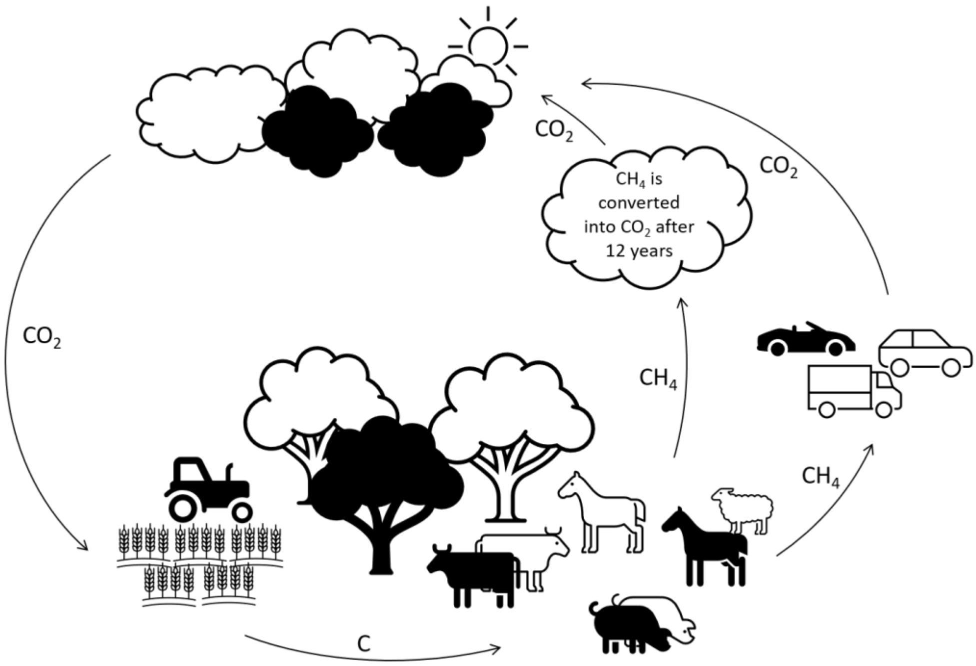

Figure 1 - The natural CH_4-cycle, including energy use

Background

In 2019 an investigation of the biogas situation in Sweden was handed over to the Swedish government. The investigation, called “More biogas!”, advocates more production of biogas from food waste, manure, and other organic waste materials (Regeringen, 2020-09-14). In September 2020, the Swedish government decided to allocate 200 million SEK in the 2021 budget, to support development of biogas production (Regeringen, 2020-09-14).

Biogas is naturally produced in nature by anaerobic digestion of organic materials and consists of 45-85% methane and 15-45% carbon dioxide depending on the circumstances (Naturvårdsverket, 2012, p.18). To make the biogas into fuel for cars, the carbon dioxide needs to be removed so that the amount of methane is no less than 95% of the remaining gas (Naturvårdsverket, 2012, p.24). In common parlance, the term biogas is both the raw gas from the production, with low amount of methane, and the purified gas with a high amount. But in a technical language only the raw gas is called biogas, whereas the purified gas, which can be used as fuel, is called bio-methane and so it will continue in this report.

Bio-methane has the same amount of methane as the fossil alternative, natural gas, and they are often mixed in a gas grid to be used as vehicle fuel or to produce heat and electricity in power plants. Today most of the gas fuelled vehicles are using compressed gas (CNG/CBG) but a market for liquid natural gas (LNG) and liquid bio-methane (LBG) has started due to demand for bio-methane as a fuel in the transport sector. To make the methane liquid the gas is cooled to -163^{o}C and must be stored at the same low temperature (Naturvårdsverket, 2012, p.47). The compressed gas, used for vehicles on the Swedish market, did in the beginning of 2020 consist of 95% bio-methane and only 5% natural gas (Energigas Sverige, 2021-02-15).

To produce biogas there are two main procedures, gasification or anaerobic digestion. Gasification technology is a process where biomass, often from wood material, is heated with a controlled temperature and a controlled amount of oxygen to produce CO, H_2, CH_4 and C_2H_4 (Energigas Sverige, 2020-02-12). The second procedure, anaerobic digestion, consists of microorganisms breaking down biomass in an oxygen free environment, for example in the stomach of a cow. This process is also used in industry, and the technology of this process is often explained as a huge mechanical cow stomach.

This report will focus on the anaerobic digestion facility in Borås, Sweden, which today handles the organic household waste from the nearby region to produce biogas. The facility is deploying some new technologies during 2021 that gives the possibility to receive and handle a bigger volume of material than today and this report will investigate that possibility. There are several organic waste materials in society that are not used but can be used to produce biogas. By making use of the energy in these materials our world gets closer to a fossil free energy supply.

Biogas production by anaerobic digestion

Anaerobic digestion is a process that depends on the interplay between different types of microorganisms. Under the right circumstances this takes place in nature every day but not in an efficient way. By creating the right circumstances for the process, it is possible to make large scale biogas production and make it efficient.

Biochemistry behind anaerobic digestion

The anaerobic digestion process can be divided into three steps; hydrolysis, fermentation and methanogenesis (see Figure 2). There are several different microorganisms that are responsible for these three steps (Avfall Sverige, 2009, p.7). In the hydrolysis step the organic material is degraded into sugars, amino acids and fatty acids by enzymes which are produced by the microorganisms (Achinas S., 2020, p.18). The required time for this step depends on the type of material, some materials take a long time to degrade into smaller molecules and others do not (Avfall Sverige, 2009, p.7).

In the fermentation step the microorganisms degrade sugars, amino acids, and fatty acids, into hydrogen (H_2), carbon dioxide, and acetic acid. In some cases, the fermentation needs to be divided into two steps, acidogenesis and acetogenesis. The acidogenesis step produces the intermediate products, such as carbonic acids, or alcohols, which are later transformed into hydrogen and carbon dioxide or acetic acid through the acetogenesis step (Achinas S., 2020, p.18).

At last, the methanogenesis step produces methane and carbon dioxide from the hydrogen, carbon dioxide and the acetic acid, the result is called biogas. The organic material which is left and not degraded is called digestate. The digestate is flavourless and can be used as fertilizer on farmlands as an alternative to animal manure and can even replace some mineral fertilizer (Avfall Sverige, 2009, p.78).

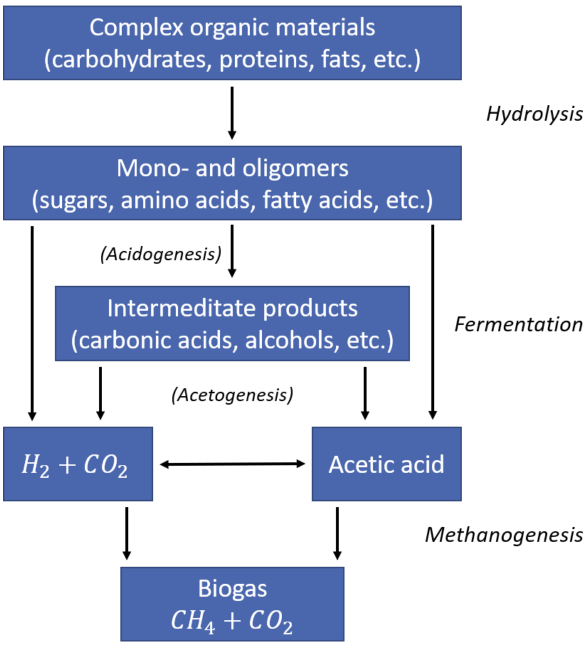

Figure 2 - The three steps of anaerobic digestion

An important consideration is the ratio of carbon (C) to nitrogen (N) in the material, the C/N-ratio. An organic material with a large amount of carbon, for example straw, creates a nitrogen deficiency for some of the microorganisms and leads to fast hydrolysis and fermentation, in which case the methanogenesis step cannot keep up (Avfall Sverige, 2009, p.41). A material with too much nitrogen, for example pig-manure, gives a low C/N-ratio and can instead be inhibitory for the methanogenesis step (Avfall Sverige, 2009, p.43). So, if the C/N-ratio is too high or too low the methane production is affected negatively. Therefore, it is important to find a good C/N-ratio for the process, unfortunately the perfect C/N-ratio is individual for different material mixes and process conditions (Avfall Sverige, 2009, p.35).

Technology in anaerobic digestion facilities

There are currently about 280 anaerobic digestion facilities in Sweden, nearly half of them are treating sludge, a by-product from wastewater treatment plants, 18% is located at farms and 13% are co-digestion facilities (Klackenberg L., 2020, p.3). Co-digestion facilities are the ones which make biogas from more than one organic material, for example different animal manure or household waste. Even though the number of co-digestion plants are small, they produce approximately half of all produced biogas in Sweden (Klackenberg L., 2020, p.9).

Most of the digestion plants today handle the organic material by making it a slurry, e.g. by mixing it with water. The liquid feedstock is then pumped into a digester, where the anaerobic digestion takes place, which can be seen in the middle of Figure 3. It is important to have a slow stirring of the slurry inside the digester. From the top of the digester the biogas leads out and from the side the treated material, the digestate, is let out (see Figure 3). Today all digestate from farm based facilities and co-digestion facilities is used as fertilizer on farmlands (Klackenberg L., 2020, p.21). The biogas can either be combusted directly in an engine which produces electricity or be purified in an upgrading facility into bio-methane.

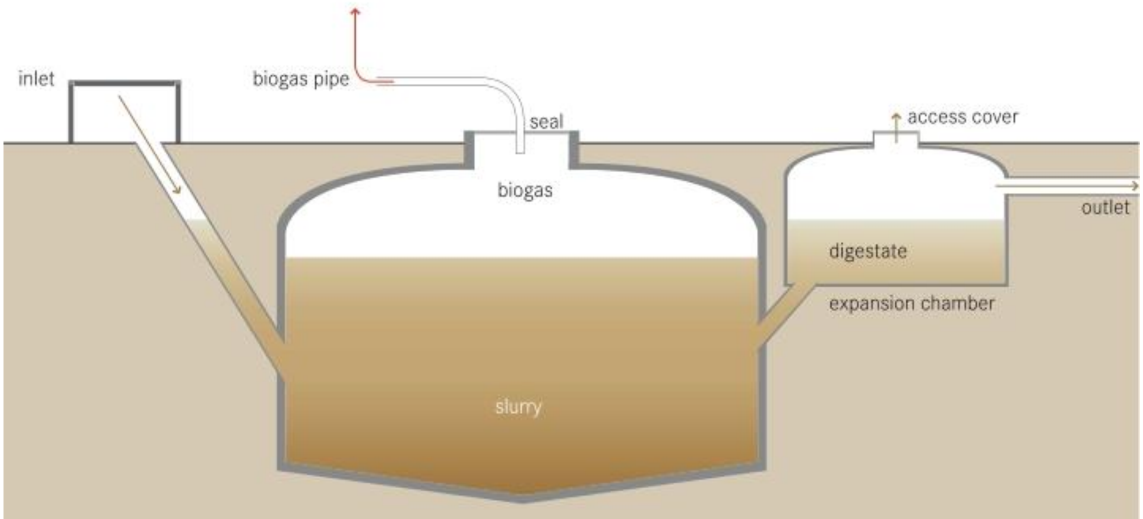

Figure 3 - Schematic of a simple biogas reactor (Tilley E., 2014)

To make the microorganisms in the digester grow and flourish it is important to keep the temperature of the slurry constant, either with a mesophile digestion at ~37°C or with a thermophile digestion at ~55°C (Avfall Sverige, 2009, p.22). The slurry is calculated to be in the digester for 30 days, but for a single particle this can vary. In most facilities, where the digestate is spread on farmlands and the organic material is contained from different places, it is important to hygienizate the material to make sure that viruses and bacterial diseases are killed. This can be done either by heating the slurry to 70°C for 60 minutes or using a thermophile digestion with a secured hydraulic retention time of at least 10 hours (Avfall Sverige, 2009, p.86).

The facility of "Borås Energi & Miljö"

"Borås Energi & Miljö" (BEM) is a public company, owned by the municipality, with the main purpose of serving the inhabitants with waste handling, sludge treatment, drinking water and district heating. The largest facility of BEM, "Sobacken", is located a few kilometres south from the city of Borås. On this site there are several different sub facilities with their own organisation; one bio fuelled power plant, one wastewater treatment plant including sludge treatment, one landfill area, the anaerobic digestion plant for household waste and one upgrading facility which produces bio-methane. The anaerobic digestion of sludge is done in connection with the sludge treatment and is handled by that sub organisation, so there are two different biogas producers on the site.

There is today a small upgrading facility at the site which produces bio-methane, but the plan is to let a commercial company build a larger upgrading facility at the site of Sobacken. BEM will then be a raw gas producer that only produces biogas. The upgrading into bio-methane and the logistic solutions are handled by the commercial company. The bio-methane is today both used to fuel the waste-collection trucks, which are owned by BEM, and is also transported into the city of Borås by a pipeline to fuel personal cars.

The anaerobic digestion plant that handles the household waste is a co-digestion facility that has been developed and expanded several times. During the early summer 2021 a huge reconstruction will be completed with new technology, even though some parts of the plant constructed during the 1990s will remain. The facility that will be launched will have an improved capacity to make use of all the organic material that is received. The old technology had some difficulties separating inorganic material, such as plastics, and therefore much of the organic material followed the inorganic material to incineration. The new pre-treatment technology is supposed to increase the amount of organic material that ends up in the digester from 50% to 80-85%, but there is currently no data to confirm the actual amount (Robert Kjellstrand, 2021-02-03). Since this report will discuss future developments of the biogas facility, only the new technology which will be launched in 2021 will be presented.

The biogas facility launched 2021

The process flow of the facility at Sobacken can be seen in Figure 5. The material flow starts when the organic waste is received at the biogas facility of Sobacken. The organic household waste is dumped from a truck into a bunker in the receiving hall. The households are mainly sorting their organic waste into paper bags which will be degraded in the process. Solid organic waste from supermarkets and food production sites, both packed and unpacked, is also dumped into the bunker. The material in the bunker is transported into a combined dissolver and separator, a pulper, with the purpose of dissolving the organic material and separating inorganic material. Out from the pulper there is one feedstock containing a mix of water and organic material, called a slurry, and one feedstock with solid material that will be sent to incineration containing mainly plastic, metals and solid organic materials, such as wood.

The combined dissolver and separator is a “Grubbens HC-Pulper” (see Figure 4) and is only using centripetal forces to demolish the soft organic materials into smaller parts, no mechanical forces like in the case of a mill are used. The material is sent batch-wise into the separator-tank, shaped as a standing cylinder, and is then mixed with water. To become a slurry a propeller starts to rotate in the bottom of the cylindrical tank and make the mixture rotate inside the tank. The shear force will pull the soft organic materials into smaller parts but the hard and strong materials, such as rocks or plastics, will remain solid. After a certain time, the mixture has become a slurry containing some solid materials and is floating out of the tank through a sieve with 6mm holes to separate the solid materials. The solid materials are collected and sent to be incinerated. To thicken the slurry, after the strainer, a second separator removes some of the water and sends the water back into the pulper while a thicker slurry is pumped into the buffer tank.

Figure 4 - "Grubbens HC-Pulper", showing the propeller in the pulper (Cellwood Machinery)

From the buffer tank the slurry is pumped into the first out of two digester tanks, both of them has a volume of ~3000 cubic meters. The buffer tank makes it possible to have a continuous feeding of the digester tank all the time, even at nighttime and weekends when there is no organic material dumped into the receiving bunker. The continuous feeding and a slow stirring of the digester tank is important to ensure a good biogas production. If the microorganisms in the digester process are lacking in new material some of them will die and the remaining ones will need time to reproduce before the feeding can increase again (Avfall Sverige, 2009, p.25). In the first digester the main digestion process takes place and in the second digester tank, the post-digester, the material is degraded further. The anaerobic digestion process is the same in both tanks, but the second tank ensures that a higher amount of the possible biogas yield is extracted.

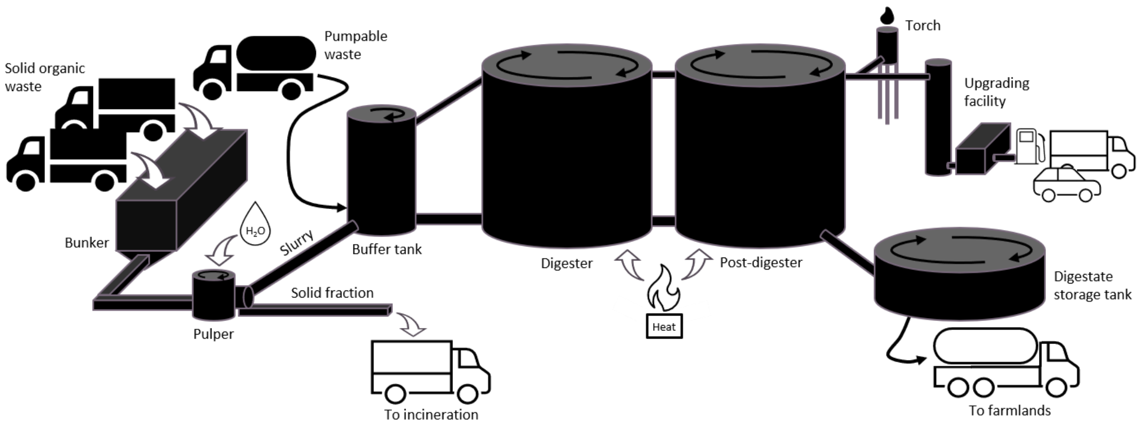

Figure 5 - Flow sheet for the digestion facility at Sobacken (full size figure in Appendix 2)

At Sobacken it is also possible to leave pumpable organic waste with tank trucks. The pumping system is dimensioned to unload some trucks per day, but not for continuous unloading.

The anaerobic digestion at Sobacken is a thermophile process that runs at 53-54°C and to ensure a safe hygienization of the material the slurry needs to be kept at this temperature for at least 10 hours. This happens in the post-digester by feeding the tank batch-wise with 10 hours delay and before a new batch is inserted some hygienizated slurry is pumped out. The slurry that comes out from the digester, the digestate, is pumped into the digestate storage tank. The digestate is sent as biofertilizer to farms and the transport of the digestate to the farms is done with trucks.

The received material today

The household waste which is received today comes from several municipalities in the surrounding area, even though the facility is owned by the municipality of Borås. The municipalities which send their waste to Sobacken are Bollebygd, Mark, Ulricehamn and even Uddevalla. While the new technology is launched in 2021 the households in Borås start to sort their organic wastes in paper bags and throw them in separate bins. The paper bags degrade in the anaerobic digestion process, unlike plastic bags, and there will only be a small amount of inorganic waste which needs to be sorted out from the received material.

Both the municipality of Bollebygd, west of Borås, and the municipality of Mark, south of Borås, are sorting their household waste in separate bins. In the municipality of Ulricehamn, east of Borås, the old system which has been used in Borås for several years is implemented. They sort their incineration waste in white plastic bags and their organic waste in black plastic bags. Both the white and the black plastic bags are thrown in the same bin and are sorted at Sobacken. In the future, the sorting system of white and black plastic bags at Sobacken will be taken out of service and BEM will not be able to receive the household waste unsorted anymore.

Uddevalla is a municipality about 150 kilometres northwest of Borås which also lets its inhabitants throw their organic waste in a separate bin. In a local waste handling site, the organic waste from the region near Uddevalla is collected in containers and transported to Sobacken. There are about 3 trucks, containing 35 tons, every week which leave organic waste from Uddevalla in the receiving bunker at Sobacken.

Aim

Until the summer 2021 there has only been one digester tank in use at a time. From now on, the two tanks will be used in series and one of them will work as a post-digester. This reconstruction leads to a doubled digester volume in total. Even though the hydraulic retention time for the slurry will be some days longer with two digesters, the higher volume makes it possible to receive more material and produce more biogas. All the organic household waste from the region is already handled in the facility, so there is a need for some other waste materials. Some materials can easily be received, others may require some external technology to handle. This report will investigate the possibilities to make use of other organic waste materials than household waste to produce biogas at Sobacken.

THEORY

In this chapter the most common organic waste materials in the region are investigated. Inevitably, most of them are different types of manure from animals, but it is also waste from food production. The following sections will present the potential of producing biogas out of these organic materials. It will explain the most common way of manure handling and the theoretical gas potential from the different organic materials.

Introduction to the most common organic wastes

Manure from animals is often used only as a fertilizer even though it contains potential energy in terms of methane. The manure has different characteristics depending on which type of animal it comes from, both in relation to handling of the manure at the farm and in the digestion process.

Cattle manure

The most common type of manure in Sweden and so even in the west coast area ("Västra Götaland") is cattle manure, in 2008 it was 67% of the total manure from farms (Linné M., 2008, p.44). The percentage is probably a little lower today because of a higher number of horses and a bit fewer milk cows (ATL, 2017), but cattle manure is most likely still the majority. Cattle manure can be handled as a pumpable slurry or as a solid fraction that can be dug out from the stable with a tractor. More than 80% of cattle manure from milk cows is handled as a slurry and so is ~40% of the manure from other cattle (Andrist Rangel Y., 2014, p.12). The solid manure often contains bedding material of straw and the amount of urine and dung can vary. A higher amount of bedding material leads to a higher C/N-ratio, which often has a positive effect for the digestion of cattle manure. Unfortunately, the straw can produce a floating cover at the top, inside the digester, and inhibit the biogas production (Olsson H., 2014, p.7).

Cattle naturally emit methane by the fermentation process in their stomachs and even the manure emits methane (IPCC, 2013, p.509). The methane related to cattle and other ruminant animals is one of the largest emission sources of methane in the world (IPCC, 2013, p.509). However, in Sweden 98% of all the manure storage for cattle sludge is covered (Andrist Rangel Y., 2014, p.12). The reason for this is to prevent leakage of important nutrients and even some gas emissions during storage. Cattle manure is normally used as fertilizer on the farmlands where the cattle food is grown.

Cattle sludge is a common material to use in biogas production. The gas potential is not especially high but because the anaerobic digestion starts in the stomach of the cattle, continuing the process becomes easy. Moreover, the pumpable slurry makes the technical solutions simple, so an anaerobic digestion facility of cattle manure is easy to implement even on a small scale. Today there is great knowledge about making biogas out of cattle manure. The techniques are implemented in some places in Sweden but are still quite rare so there is still much cattle manure which is not used for biogas production.

One reason for this is the large investment for the farmers and even the lack of time that farmers often have, especially during some parts of the year. Some anaerobic digestion facilities which use cattle sludge transport the sludge with a tank truck from several farms, but it can be difficult to source it in a financially feasible way (LRF, <2012, p.10).

In environmental discussions the cattle are pointed out as one of the largest pollutants of greenhouse gases. But it can be discussed whether the greenhouse gases from cattle are harmless or not, because they are still only substances in the natural cycle. However, manure from cattle is naturally emitting methane and the environmental benefits of containing the methane are good (Tufvesson L., 2013, p.43). If the produced biogas also can replace fossil fuels, the environmental benefits will be doubled (Tufvesson L., 2013, p.43)

Pig manure

The Swedish pigs are some of the most healthy pigs in the world, this is because the regulations for pig farms in Sweden are even tougher than the EU-regulations (LRF, 2017, p.3, 5). Unfortunately, this leads to high costs for Swedish pig farms and therefore they are quite few, only 1% of the pigs in the EU is from Sweden (LRF, 2017, p.2).

Most of the manure from pig farms in Sweden is collected as a slurry. This is because it is legal for all farms, even ecological and KRAV-certified, to have parts of the box floor with small gaps for the droppings to fall down (LRF, 2017, p.5). But there is also a requirement to have an area with bedding material in the boxes (LRF, 2017, p.5). In a conventional farm the bedding material can be so sparse that it can be mixed into the slurry, but in an ecological or KRAV-certified farm the amount of bedding material is too high and is mostly handled as solid manure. Regardless of if the manure is handled as slurry or solid manure, it is used as fertilizer on farmlands connected to the farm.

Pig manure has a high amount of nitrogen and that makes the C/N-ratio low enough to inhibit the methanogenesis step (Nagy G., 2012, p.70-71). The manure from pigs also contain a lot of minerals which result in a higher risk for sedimentation (Carlsson M., 2009, p.14). However, the pig manure is a manure with higher gas potential than manure from ruminants, like cattle (Carlsson M., 2009, p.14). The gas yield is especially high from pig manure if it is co-digested with materials with a higher amount of carbon, the biogas production can increase by as much as 11-fold with this type of co-digestion (Wu X., 2010, p.11-12).

Horse manure

Until April 2021 it has not been necessary to register horses in Sweden, so it has been difficult to know the actual number of horses in the country. But it has been clear for a long time that horses often live in areas near societies and that has sometimes caused problems handling the manure (Malgeryd J., 2013, p.5). Horse owners living near societies often buy horse food and have therefore no use of the manure. Instead, it can be necessary to pay someone to take care of the horse manure. In 2016 the number of horses in Sweden was approximated to 355 500 and the second most horse-dense region in Sweden was the west coast area ("Västra Götaland"), with 56 400 horses (ATL, 2017).

About 10% of the animal manure in Sweden is from horses and it is important that nutrients left in the manure are returned to the farmlands in a controlled way and does not run off with rainwater into nearby waterways (Malgeryd J., 2013, p.5-7). According to a study 2008, horse manure relates to 17% of the total biogas potential from animal manure (Linné M., 2008, p.54).

During horse keeping a large amount of bedding material is used and if the keeper is not aware, a large amount of the manure can at the end consist of bedding material instead of dung (Malgeryd J., 2013, p.12). To make the manure easy to degrade it is important to keep the amount of bedding material low in the manure and only pick out the droppings and the wet bedding material from the stable. The most common bedding material is straw, peat, or saw dust, but the use of pellets from straw as bedding material starts to become common (Olsson H., 2014, p.10).

A facility in Töreboda has tried co-digestion with a mix of horse manure and cattle manure and the result shows that some bedding material can translate to problems with sedimentation, and others to making a floating cover at the liquid surface (Olsson H., 2014, p.14,25,35). The best bedding material to use if the manure should be used in a biogas process is the straw pellets (Mattsson M., 2015, p.34, Olsson H., 2014, p.40). The straw pellet becomes pulverized when it is trampled by the horses, the pulverization leads to a good absorption (Mattsson M., 2015, p.8). The pellet is possible to degrade in an anaerobic digestion process and is therefore also producing biogas, moreover it does not cause problems in the process (Mattsson M., 2015, p.10-13).

Studies do show that when using straw pellets as bedding material less of the bedding material follows the manure and the manure gets a higher proportion of horse dropping (Mattsson M., 2015, p.25). Using peat as a bedding material can be an alternative to straw pellet when it should be used in a biogas process, but the properties seem to be less favorable (Olsson H., 2014, p.7,17-18). However more studies need to be done before peat can be dismissed.

Pure horse manure has the highest gas potential during the first days, but this is not true for bedding material with straw pellets (Mattsson M., 2015, p.27). Horse manure with straw pellet as bedding material shows the highest gas potential after one month storage and after two months that potential is halved (Mattsson M., 2015, p.27).

It is important that the manure that is used in the biogas process is only collected inside the stable on a solid floor to ensure as clean fraction as possible. If the manure also is collected in the pasture the risk of including rocks and gravel is high and that will settle at the bottom of the digester tank (Mattsson M., 2015, p.13). Manure from the pastures can either be spread directly on farmlands or be composted.

Chicken manure

The manure from chickens often consists solely of droppings due to the way it is collected and transported from the stable, but can also contain a negligible amount of bedding material (Litorell O., 2005, p.8, 11-12). The animal keeping can look quite different at chicken farms and the regulations depend on which types of stable system that is used, some farms use bigger bedding areas in the stable than others (Litorell O., 2005, p.11-12). The bedding material is usually hacked straw, peat, or saw dust and is dug out when the chickens are transported to slaughter (Litorell O., 2005, p.12). In many stables there are some areas with a net that the chicken can sit on. Under the net there is a collecting system for droppings. The layout in the stable makes the chicken spend much of their time sitting on the net which leads to the majority of the droppings ending up below the net instead of in the bedding material (Litorell O., 2005, p.12). Chicken farms normally do not grow food for the chickens on their own and are therefore not using the chicken manure.

Chicken manure has a high gas potential and is therefore an attractive source for biogas production (Jurgutis L., 2020, p.9). However, chicken manure has a high amount of nitrogen which leads to a low C/N-ratio (Wang X., 2014, p.1-2). A study of an anaerobic digestion with a large amount of chicken manure shows that the biogas production is inhibited by the low C/N-ratio, but the C/N-ratio can be increased with other organic materials (Wang X., 2014, p.6). If the C/N-ratio is regulated with other organic materials in a co-digestion process the gas potential from chicken manure can be well used (Wang X., 2013, p.172-173). However, the high amount of nitrogen makes chicken manure highly sought-after as a fertilizer and therefore the biogas facilities need to pay the market price to receive it (Edström M., 2018, p.7). Moreover, the high amount of lime in chicken manure has led to some sedimentation problems in biogas facilities and because of that some facilities have stopped receiving chicken manure (Edström M., 2018, p.7,24).

Food waste

For several years it has been well known that it is possible to produce biogas out of organic household wastes and other types of food waste. Many countries in the world have banned food waste in landfills and therefore biogas production is a good alternative way to handle it (Zhang C., 2014, p.384). The high percentage of dry matter (TS) and volatile solids (VS) in food waste result in a high biogas yield during anaerobic digestion even though these vary with the content of the waste (Zhang C., 2014, p.384). However, it is clear that food waste generates significantly more biogas than the sorts of manure described above (Carlsson M., 2009, p.24-27).

To increase the biogas production from food waste, the C/N-ratio can be regulated to a value that fits the specific organic mixture (Zhang C., 2014, p.386). To regulate the C/N-ratio, food waste can be co-digested with different sorts of manure (Zhang C., 2014, p.386). For example, co-digestion with cattle manure, with a 2:1 ratio of food waste to cattle manure, can increase the biogas yield by 40% (Zhang C., 2013, p.175).

Biogas potential of the materials

As described in the beginning of the Theory-chapter the materials have different properties and the possibilities to produce biogas differ. To know how much substance there is in a material the “Total Solid” value (TS) needs to be determined. The TS-value represents the percentage of the remaining weight when the water is totally evaporated from the material (Carlsson M., 2009, p.7). Manure which is handled as a slurry has a low TS, below 10%, and solid manure has a higher TS, between 20-40% depending on the amount of bedding material and manure type (Table 1). Moreover, cattle and pig farms which use larger volumes of water during cleaning of animals and stables are lowering their TS value of the manure slurry (Thomas Sylvesson, 2021-04-01).

To convey how easily degradable the material is, the “Volatile Solid” value (VS) represents the organic compounds of the material (Carlsson M., 2009, p.7). The VS percentage of the TS value signifies the proportion of the material substance which can be degradable and produce biogas. For manures, the value is often about 80%, and for food waste it is little higher, about 90% (Table 1).

In both the Background-section and the theory-parts about pig and chicken manure the effect of C/N-ratio is described. Table 1 shows that especially pig and chicken manures have a low C/N-ratio, below 10, and food waste has a high C/N-ratio between 15-32. However, in the existing digestion facility at Sobacken, the C/N-ratio varies between ~10-16, even though the clear majority of the received material is food-waste from households (see data in Appendix 3).

The percentage of methane (CH_4) in the produced biogas is normally about 65% but is a bit less for horse manure (Table 1). The potential methane volume which can be produced from the organic mass of the material is expressed as produced methane volume per ton VS. Cattle manure has a low gas potential since the anaerobic digestion has already started in the stomach (Avfall Sverige, 2009, p.48). Pig and chicken manure has a high gas potential, but the low C/N-ratio can make it tricky to reach the potential yield. Due to this low C/N-ratio, pig and chicken manure are advocated to be co-digested with materials that have a higher C/N-ratio (Wu X., 2010, p.11-12, Wang X., 2013, p.172-173). However, all anaerobic digestion processes become more stable and proceed closer to the limit of their gas production potentials if the materials are co-digested (Carlsson M., 2009, p.16). Food waste has a significantly higher gas potential than manure because all the energy remains in the material and no animal has processed it.

One further property to consider is the methane volume of the wet weight (WW), which is especially important regarding the transportation of the material. A material with a low methane volume per wet weight can possibly reach a negative net energy when comparing the energy extracted from the material to the energy used for transportation. Manures handled as a slurry have significantly lower gas volume per wet weight due to the large proportion of water in the material.

Table 1 - Digestion properties for different materials

Sort of material	TS of WW	VS of TS	C/N-ratio	CH_4 in biogas	Nm^3 CH_4/ ton VS	Nm^3 CH_4/ ton WW
Cattle manure (slurry)	8-10% [1,6,7]	75-84% [1,7]	6-20 [1]	65% [1]	190-213 [1,6*]	14 [1*]
Pig manure (slurry)	6-8% [1,2]	80-81% [1,2]	5-8 [1,9]	65% [1]	247-268 [1,6**]	17 [1*]
Horse manure	20-30% [2,3,4]	76-88% [2,3,4]	13-23 [2]	52-55% [4]	170-200 [2,4]	41-68 [4]
Chicken manure	32-43% [1,7,8]	62-81% [1,7,8]	3-10 [1]	62% [8]	247-312 [1,8]	89 [8]
Food waste (households)	19-33% [1,10]	85-92% [1,10]	15-32 [1,10]	63% [1]	410-461 [1,10]	125 [5]

[1] (Carlsson M., 2009, p.24-27*) *transformed from Nm^3 biogas into Nm^3 CH_4; - [2] (Mattsson M., 2015, p.11,21,24); - [3] (Henriksson G., 2015, p.19); - [4] (Wennerberg P., 2013, p.32); - [5] (Linné M., 2008, p.9,52); - [6] (Tufvesson L., 2013, p.53*) **transformed from TS to VS by "VS of TS"; - [7] (Edström M., 2018, p.14); - [8] (Jurgutis L., 2020, p.5); - [9] (Wu X., 2010, p.2); - [10] (Zhang C., 2013, p.171-172)

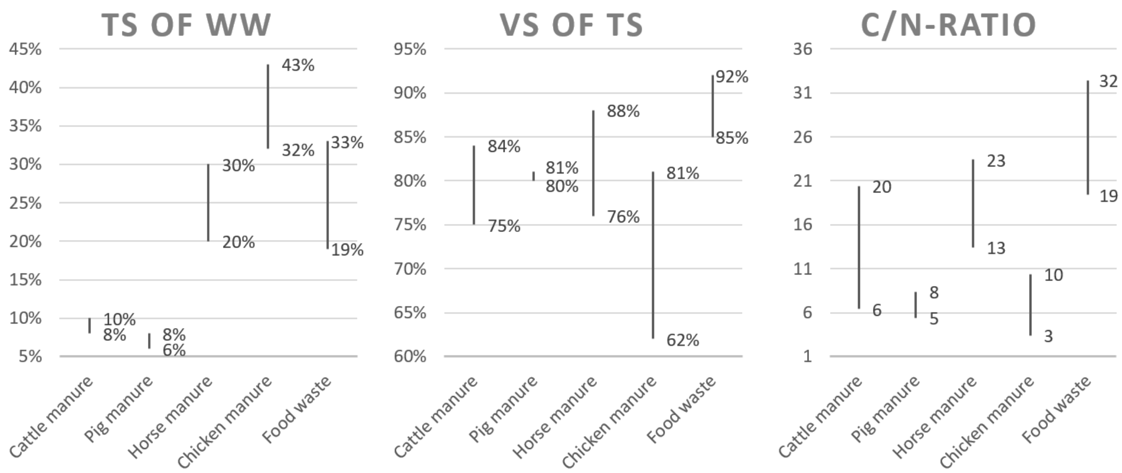

Figure 6 - Graphically showed TS, VS of TS, C/N-ratio

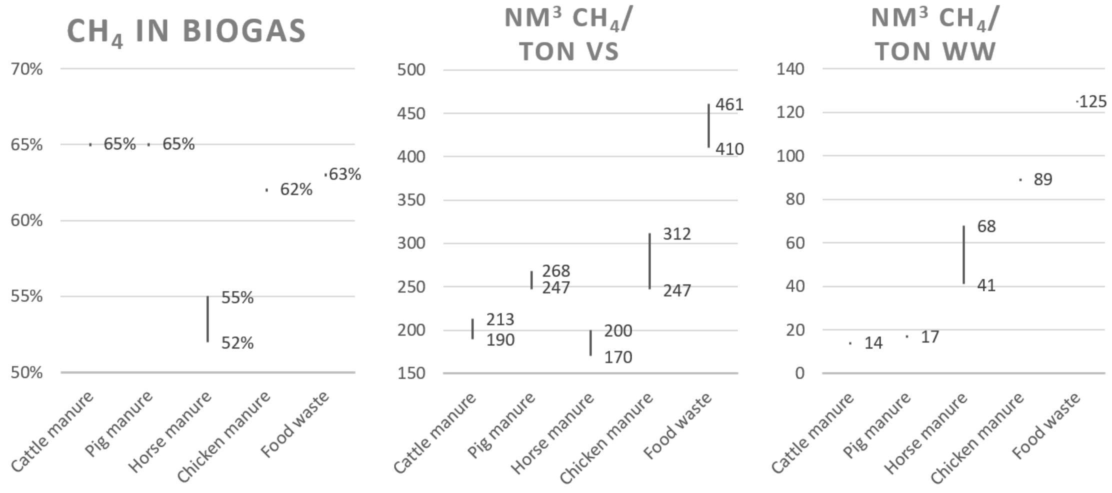

Figure 7 - Graphically showed CH_4 in biogas, Nm^3 CH_4/ton VS, Nm^3 CH_4/ton wet weight

ANALYSIS

In the following chapter an analysis of the organic wastes in the region will be presented. The first part is about which organic materials can be found in the region close to Sobacken. This part includes a map and an analysis of the farms location in the region. The issues relating to handling manure from KRAV-certified farms are also declared. Moreover, the technical solutions which are required for receiving and transporting the new material types are presented. At the end of this analysis-chapter, calculations of the possible transport distances for each new type of organic material are presented.

Potential organic waste in the region

It is important to consider the location and the technology of a co-digestion facility when investigating the expansion of biogas production. The conditions are not the same at every site and the amount of a specific type of organic waste is not equal across regions. In the close surroundings of Sobacken there are some uncommon waste materials and others quite common. There are several different animal manures such as horse, cattle, chicken and even a mix of manure from the local zoo. Moreover, there are both small and big food productions in the region which also produce organic waste. Some producers already send their waste to Sobacken. In the following section the potential of different organic waste materials from the region will be investigated.

Food producers

As in every region there are industries in Borås which produce or handle food. From all food handling there is waste. Some organic wastes from food production, such as slaughter waste, have higher biogas potential than others and therefore can be sold. For example, the big slaughterhouse east of Borås, "Dalsjöfors Slakteri", sells their waste to biogas facilities (Robert Kjellstrand, 2021-02-03). Slaughter waste has a methane potential of 547 Nm^3 CH_4/ton VS, which is 18,7% higher than for food waste from households (Carlsson M., 2009, p.24-27). Due to the knowledge about the high gas potential from slaughter waste, both from biogas facilities and slaughterhouses, this waste material is not analysed further in this report.

However, for small food producers it is not always as easy to get rid of the organic waste since it is not as valuable. In many industries, disposing of organic waste is just a burden. But organic waste from food industries is often good for biogas production and can be an important energy resource for the society. If the food does not reach the standards for human food, nor for animal food, biogas production is a good way to still make use of it. If it is possible to sort it as pure organic waste already in the production, the handling at the biogas facility will be even easier and more efficient.

Zoo manure

In the northern part of Borås city there is a zoo which holds both Nordic-native animals and African-native animals (Borås Djurpark, 2021-04-28). Of course, the animals at the zoo produce a lot of manure. However, there is a mixture of several different types of manure, and it is hard to generalise it all as zoo manure. Much of the manure probably has similar properties as the manure types in the section "Introduction to the most common organic wastes", but surely there are special fractions too. For example, elephant droppings consist of some branches and fibres which are hard to degrade in a biogas process (Henriksson G., 2015, p.35).

One problem for biogas facilities if they should use the manure from the zoo is the same as from horse manure, the high percentage of bedding material. Because the aim of the zoo is partly for the visitors to see the unusual animals, it is probably important for the zoo to show a cosy and clean box. Therefore, the zoo might use a lot of bedding material for their animals and the proportion of dung in the manure becomes quite low. Moreover, if the bedding material consists of straw, the manure becomes hard to handle in a biogas facility due to the risk of a floating covering in the digester.

Some of the manure fractions from the zoo are surely good for biogas production. If the zoo starts to use straw pellet as bedding material and handled the droppings in a way which ensures a high amount of dung, the manure may become possible to use in a biogas production. However, this needs to be studied further for every single type of manure.

The map of farms in the region

The four focused manure types in the section "Introduction to the most common organic wastes" are from cattle, pigs, horses, and chickens. These are also the most common types of manure in the region surrounding Sobacken. Figure 8 shows the locations and the number of farms in the region. The colour and size of the dots signify animal type and the number of farms, at the specific postcode. For example, the smallest yellow circle signifies one chicken farm and a white circle with a "7" signifies seven cattle farms at that postcode. The marks are placed in the middle of the postcode area so the actual location of the farms can vary. In Figure 8 there is also a marked area which represents the driving distance of 30 kilometres from Sobacken, this is to get a perspective of the distances.

The marked cattle farms and pig farms hold 50 animals or more, the horse farms 10 horses or more, and the chicken farms 500 chickens or more. The data which are visualized on the map in Figure 8 are sent from Jordbruksverket and are collected in a table in Appendix 4 together with a larger scale map.

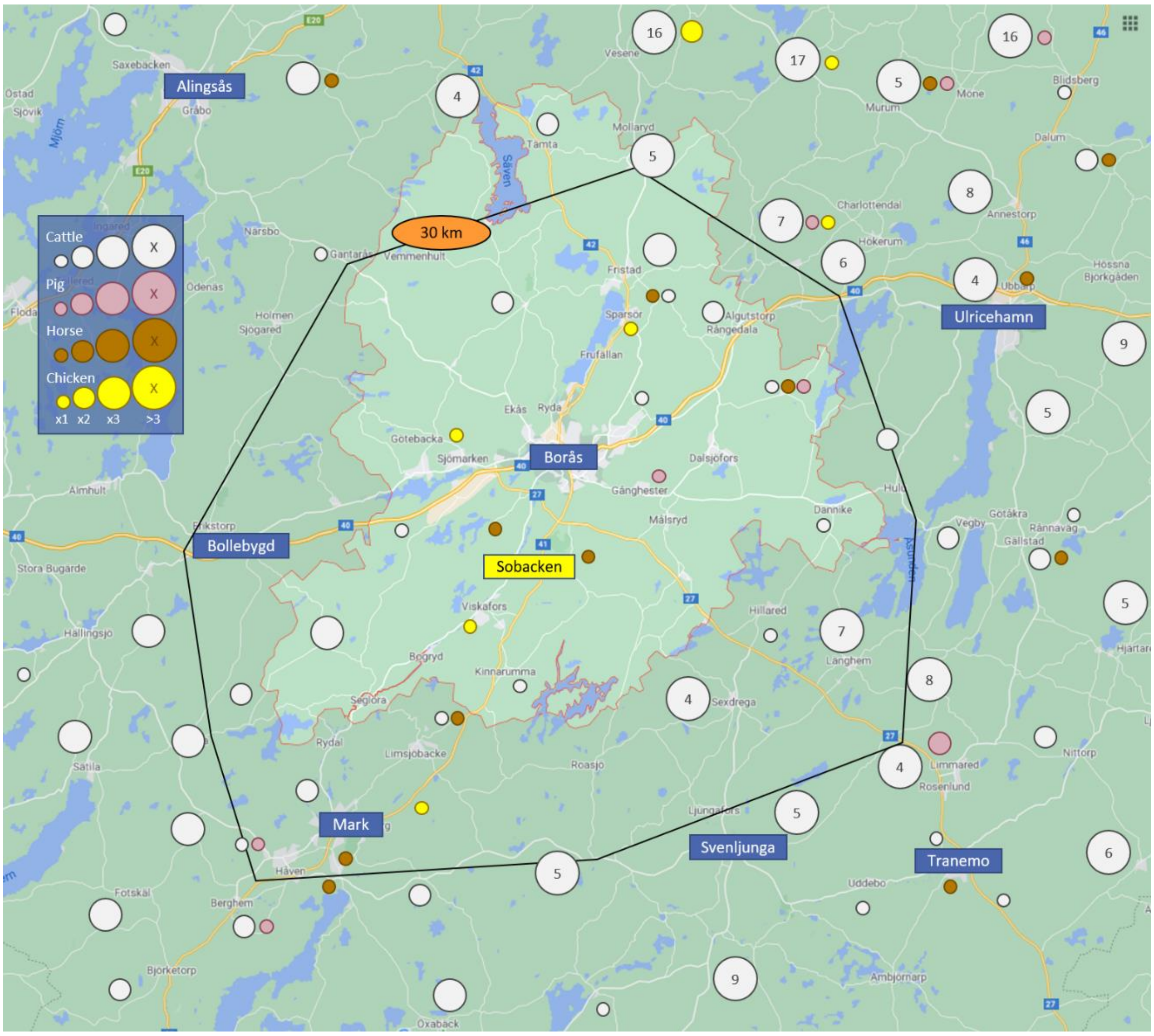

Figure 8 - Location of farms in the surroundings of Borås (full size figure in Appendix 4)

A study of Figure 8 shows a clear majority of cattle farms. In total there are 227 cattle farms marked on the map. The marked cattle farms are both farms which produce solid manure and farms producing slurry. In the north-east quarter of the map, there are 111 cattle farms which make up 49% of all cattle farms on the map. In the south-east quarter, there are 61 cattle farms, 27% of the total. The south-west and north-west quarter hold 41 and 14 cattle farms respectively, 18% and 6% of the total.

In the studied region the number of pig farms is low, there are only nine of them. After a study of the map, in Figure 8, six of the farms are between 25-35 kilometres away from Sobacken, one is closer and two are far up in the north-east corner. The marked pig farms can handle the manure either as solid manure or as a slurry.

As the theory section about horse manure declared, almost all the marked stables are in the close surroundings of societies. There are 13 horse stables marked on the map, holding a minimum of ten horses. Several stables in the region hold fewer horses but still have manure which can be collected. The map in Figure 8 can be used to see the spread of horse stables in the region and to reconfirm the theory about the locations of horse stables being close to societies.

Chicken farms which hold more than 500 chickens are marked on the map and count to eight. The marked farms can hold chickens for either egg or meat production. Several of them are located close to Sobacken.

Ecological KRAV-certified farms

According to the KRAV-organization, ”the KRAV label stands for food produced without artificial chemical pesticides, good animal welfare, reduced climate impact, more biodiversity and better working conditions” (KRAV, 2021-05-10). KRAV-standards are sometimes stricter than EU-ecological standards, mostly regarding animal handling, but are for the most part similar (Hushållningssällskapet, 2021-05-26). For farms certified by the EU as ecological farms, and for KRAV-certified farms, there are special rules regarding use of digestate as biofertilizer on farmlands. Some co-digestion facilities can deliver biofertilizer to KRAV-certified farms and others cannot, it depends on the input material to the digestion process.

Standard 12.3.5 from the KRAV-organization gives some possibilities for the certified farms to send their manure to a biogas facility and get an equal amount of biofertilizer back. For example, if the facility receives manure from the KRAV-certified farm which represents X% of the input material in the digestion process, the farm can use X% of the biofertilizer produced by the process. But for this to be allowed, there are some regulations to follow. Firstly, the biogas facility is not allowed to receive material which contain genetically modified organisms (GMO) and they are not allowed to receive manure from caged animals (KRAV, 2021c). Secondly, at least 5% of the total input material in the digestion process should be KRAV-certified (KRAV, 2021c).

Standard 12.1.2 from the KRAV-organization regulates the applications of biofertilizer for certified farms if the co-digestion is with food waste. If the co-digestion contains food waste or slaughter waste, the biogas facility in total needs to be KRAV-certified before the certified farms can use the digestate as a fertilizer (KRAV, 2021b).

Biofertilizer is a coveted fertilizer by the KRAV-certified farms due to KRAV certifications restricting use of mineral fertilizer (Kajsa Nilsson, 2021-05-06). The standard 4.8.10 forbid the usage of nonorganic nitrogen fertilizer on KRAV-certified farmlands (KRAV, 2021a). In biofertilizer the percentage of ammonium nitrite, which is easy for crops to utilize, is higher than in unprocessed manure (Avfall Sverige, 2009, p.78-79). According to several studies, biofertilizer can replace the nonorganic nitrogen fertilizer (Avfall Sverige, 2009, p.78).

Unfortunately, this has not happened on Hagelsrums farm, where a farm based anaerobic digestion facility was built more than 10 years ago. They are still in need of mineral fertilizer to produce enough animal food, although this might be related to the expansion of the farm (Tom Birgersson, 2021-04-10). At Götestorps farm a digestion process is newly installed, but the effect of using less mineral fertilizer is not fully trusted, it will just be a bonus if that is the scenario (Andreas Markusson, 2021-04-05). Nor do the conventional farms in the region of Borås see the possibility to replace mineral fertilizer with biofertilizer (Kajsa Nilsson, 2021-05-06). Today, biofertilizer mostly replace the mineral fertilizer on ecological farms and KRAV-farms, not on conventional farms (Kajsa Nilsson, 2021-05-06, Åke Ljungström, 2021-05-11).

Technical solutions to handle the new material

To make it possible to receive other organic materials than the food waste from households which are received today, some new technologies are required. Both in relation to the process at Sobacken and to the transportation of material from the collection places into the biogas facility.

Facility related solutions

At the facility today, there is a receiving system which pumps slurry out of tank trucks into the buffer tank. An unloading system which depends on a pump becomes sensitive to disturbances. To make an unloading system efficient for several unloading tank trucks every day, a receiving well is preferred. A receiving well, where the slurry can float from the tank truck, eliminates the dependency on a pump for a production critical task. From the well the slurry can be further pumped into the process without making the unloading system sensitive for pump disturbances. The well needs a stirring system to avoid sedimentation and to mix the different sorts of slurry which are received.

Solid waste, regardless of if it is manure or food waste from industries, does not require any developments of the anaerobic digestion facility at Sobacken. The solid material can be dumped into the same receiving bunker as the organic household waste is today. Water needs to be added to make slurry out of the solid material in the pulper (see Figure 9). Due to the low TS-value of manure slurry it would be possible to use it to replace some of the water needed in the pulper (Robert Kjellstrand, 2021-04-29). When manure slurry replaces water the biogas yield of the resulting slurry from the pulper will be higher. This due to the obvious fact that manure slurry has higher gas potential than water. If the water is replaced with manure slurry the need for water decreases and the benefits of the manure slurry increases.

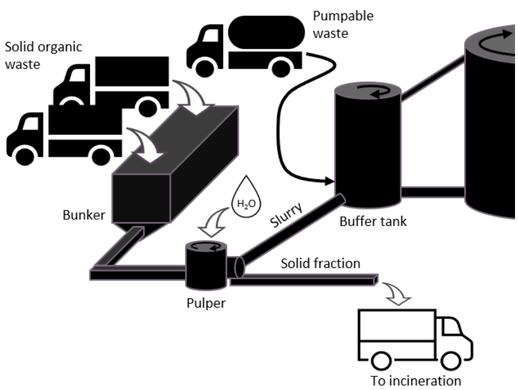

Figure 9 - Receiving part of the facility at Sobacken

There is an unused well on the site at Sobacken which historically has been used as a water reservoir for the process (Robert Kjellstrand, 2021-02-03). This well could either be used as a receiving well for manure slurry or as a mixing well for water and manure slurry. If the old well is used for mixing of manure slurry and water, before it is sent into the pulper, a new receiving well needs to be built for only manure slurry. If the old well is used as a receiving well for manure slurry, the water and manure slurry need to be mixed inside the pulper. With the second solution there is no need for a new receiving well.

Transportation related solutions

How the organic material is transported to Sobacken is a relevant question. Due to the location of Sobacken, with a long distance from most of the farms (see Figure 8), transportation by trucks is assumed to be the best solution. To not spread virus and bacteria between farms or food industries it is important to build a system, both at the collection places and at Sobacken, which avoid having the wheels of the truck in contact with the organic waste (Mattsson M., 2015, p.12). Because of this, it is important that the truck do not operate in the same area as the machines which handle the organic waste at the collection places. Moreover, the truck should have the possibility to clean the wheels on Sobacken before going to the next collection place.

Slurry

Biofertilizer and manure slurry are often transported with trucks but can also be pumped in pipelines. To make it economically beneficial to build a pipeline, much of the material should be transported on the same way and replace truck trips along this way (Tufvesson L., 2013, p.67). Due to the spread of farms in the region around Sobacken, showed in Figure 8, the preferred transportation is with trucks.

To make it possible to receive slurry from farms, the farms need to have two slurry storages. Normally a farm only has one slurry storage for manure, but now they also need one for biofertilizer. The cost of building a second storage is often the only cost for the farms, as the transportation is financed by the anaerobic digestion facility. The second storage does not necessarily need to be located on the farm. It can be located closer to the farmlands, but then the extra transport distance that this location can lead to usually needs to be paid by the farmer.

At Sobacken the unloading of the tank truck needs to be fast and easy, to reach as high efficiency as possible, preferably into a well. However, using a pump for unloading can be faster and this needs to be a possible choice for trucks which have a pumping system on the vehicle. If it is possible to let the tank truck unload manure slurry and load biofertilizer without moving between, it will be even more time efficient. A solution with pipes from the two storages, manure and biofertilizer respectively, into one location is an example of how to solve it.

To not spread virus and bacteria between farms there are also requirements to wash the inside of the tank between transporting manure from farm one and transporting biofertilizer to farm two. Even this should be possible without moving the truck, in connection with loading and unloading, to make it time efficient.

Solid material

If solid organic material is transported longer distances, it is solely transported with trucks. The trucks can either have a fixed container or be able to unload it and the truck can be with or without a crane. The different sorts of trucks are loaded in different ways. The one with a fixed container needs to be filled with either a tractor or an own fixed crane. The one with a loose container can leave the container and let the farmer or the food producer fill it whenever they want, either by hand or with a tractor. Even a truck with a loose container can have a fixed crane and a possibility to fill the container on its own.

One important thing for the collection places is to not let the solid organic waste be stored on the ground. The waste should be stored on a floor, for example made of concrete, so the risk of bringing rocks and gravel into the container is minimized. There are no issues if the organic material becomes wet by rain as long as it is possible to load with a crane fixed on the truck, or with a tractor. A wet material reduces the amount of added water needed in the process of making slurry, at the biogas facility.

According to the section "Introduction to the most common organic wastes", horse manure should not stored for more than one month to reach the highest gas yield. This means that a good solution is to collect manure from the horse farms once a month. One horse produces a little less than one cubic meter of manure per month (Mattsson M., 2015, p.30, Malgeryd J., 2013, p.16). If a horse farm should fill a container of 10 cubic meter with only manure from their own farm, they will need at least 10 horses. Farms with fewer horses will be better off storing their manure on a hard floor and let a truck with a fixed crane collect it. Additionally, not all horse farms have access to a tractor and because of that the solution with a fixed crane on the truck is a better choice.

Both food waste from small scale food industries and solid manure from animals other than horses, can be collected in the same way as horse manure. Either the organic material is stored on a hard floor and a fixed crane on the truck fills the container or the material is dumped into a loose container which is placed on the farm or the industry.

Calculation of transport distance

In this section the acceptable transport distances for different types of manure are calculated. Both the environmental and the financial sustainability for transportation are analyzed with an energy balance and a financial balance, respectively. In Table 2, some general data for methane, biogas, and bio-methane are collected.

Table 2 - Energy data for methane

	Data	Source
Methane energy content	9.97 kWh/Nm^3 CH_4	(Energigas Sverige, 2021-05-08)
Biogas percentage	65% CH_4	(Energigas Sverige, 2021-05-08)
Bio-methane percentage	97% CH_4	(Energigas Sverige, 2021-05-08)
Bio-methane energy content (kg)	13 kWh/kg bio-meth.	(Energigas Sverige, 2021-05-08)
Bio-methane energy content (Nm^3)	9.67 kWh/Nm^3 bio-meth.	(Energigas Sverige, 2021-05-08)

The calculations begin with data from Table 1, in the section "Biogas potential of the materials", to know the methane energy per wet weight, by using the following equation.

$$\frac{TS}{WW} * \frac{VS}{TS} * \frac{Nm^3\ CH_4}{ton\ VS} * \frac{kWh\ CH_4}{Nm^3\ CH_4} = \frac{kWh\ CH_4}{ton\ WW}$$

The data from Table 1 consist of one low and one high value. Therefore, one minimum and one maximum value is calculated with respective value from Table 1. In Table 3 the calculated values for methane energy per wet weight are reported. The values for methane volume per wet weight in Table 1 are inserted in Table 3, but they are transformed to have the same unit as the calculated values.

Table 3 - Methane yield per ton wet weight

kWh CH_4 / ton WW	CH_4 yield (min)	From Table 1	CH_4 yield (max)
Cattle manure (slurry)	114	140	178
Pig manure (slurry)	118	169	173
Horse manure	258	409 - 678	526
Chicken manure	489	887	1083
Food waste (households)	660	1246	1395

After a comparison of the values from Table 1 and the calculated ones, it seems like the calculated values have a good spread. Due to the importance of showing the difference between manure qualities the calculated values will be used for further calculations.

Calculation of process losses

In the process of producing biogas and upgrading it into bio-methane, there is a need for energy and there is also some leakage of gas. In Table 4 there is data about energy usage and leakage of gas, from large mesophilic anaerobic digestion processes.

Table 4 - Data about process energy and gas leakage

	Data	Source
Required process heat	25 kWh/ton WW	(Tufvesson L., 2013, p.70)
Required process electricity	7 kWh/ton WW	(Tufvesson L., 2013, p.70)
Process leakage	0,5%	(Tufvesson L., 2013, p.71)
Electricity for upgrading facility	0.25 kWh/m^3 biogas	(Tufvesson L., 2013, p.73)
Leakage from upgrading facility	1%	(Tufvesson L., 2013, p.73)
Distribution energy for bio-methane	0.033 kWh/kWh bio-meth.	(Tufvesson L., 2013, p.74)

By using the data from Table 4 the following equations can be calculated. The first one gives the used energy in the process per ton wet weight. The second one gives the leakage of methane from both the digestion process and upgrading process, expressed in energy loss per wet weight.

$$\frac{kWh\,proc.heat}{ton\,WW}+\frac{kWh\,proc.el.}{ton\,WW}+\frac{kWh\,upgr.el.}{ton\,WW}+\frac{kWh\,distr.el.}{ton\,WW}=\frac{kWh\,used}{ton\,WW}$$

$$\frac{kWh\,CH_4}{ton\,WW}*(Proc.leak.+(1-Proc.leak.)*Upg.leak.)=\frac{kWh\,leak.}{ton\,WW}$$

Together, the two equations make the total process losses for bio-methane production in the facility. Losses from transportation of material are not included in these calculations, but they will be reported later. The results of the equations above are reported in Table 5.

Table 5 - Used energy and losses due to leakage

kWh / ton WW	Energy use (min)	Energy use (max)	CH_4 leakage (min)	CH_4 leakage (max)
Cattle manure (slurry)	40	45	2	3
Pig manure (slurry)	40	44	2	3
Horse manure	50	69	4	8
Chicken manure	66	108	7	16
Food waste (households)	78	130	10	21

Both the process heat and the process electricity are related to the wet weight and not to the methane production of the material, see Table 4. This means that every type of material uses 32 kWh of heat and electricity per ton wet weight in the process. The other parameters are related to the percentage of yield biogas from the material and therefore vary for the different materials.

An uncertainty in the calculations above is the energy use for making the solid material into a slurry. This potential energy use is not considered, so the used energy for horse manure, chicken manure and food waste might be underestimated.

Impact of transport distances on energy balance

To know that the total process, including the transportation, is energy efficient, an energy balance is calculated. In the energy balance, the data about transportation from Table 6 and the previous results about energy losses in the process, reported in Table 5, are used. From the energy balance, maximum transportation distances for the materials are calculated. The transported weight of slurry per load is 32.5 tons and the transported weight of solid material is 15 tons per load.

Table 6 - Truck data

	Data	Source
Transported weight (slurry)	32.5 ton WW/load	(Åke Ljungström, 2021-05-11)
Transported weight (solid)	15 ton WW/load	(Tufvesson L., 2013, p.67)
Energy usage tank truck (slurry)	0.65 litre diesel/km	(Åke Ljungström, 2021-05-11)
Diesel energy content	9.8 kWh/litre	(Energigas Sverige, 2021-05-08)
Energy usage container truck (solid)	3.5 kWh/km	(Tufvesson L., 2013, p.67)
Loading/unloading energy	0.5 kWh/ton WW	(Tufvesson L., 2013, p.67)

The energy usage for the tank truck is high due to short transport distances including many starts and stops. In the energy usage for the tank truck it is also included the energy of loading and unloading the tank, assuming loading or unloading every 15 kilometers. Therefore, the loading energy for the tank truck is set to zero in the equation below. For the container truck the loading energy is separated from the transportation energy. The container truck is assumed to have a crane and use energy during loading with the crane but not when dumping the solid material into the receiving bunker.

$$\frac{\left(\left(\frac{kWh\ CH_4}{ton\ WW}-\frac{kWh\ used}{ton\ WW}-\frac{kWh\ leak.}{ton\ WW}\right)*\frac{ton\ WW}{load}-\frac{kWh\ loading}{load}\right)}{\frac{kWh\ diesel}{km}*2}=\frac{single\ dist.}{load}$$

To get a maximum transportation radius from Sobacken, even seen as a single way distance, the total transportation distance is halved in the equation above. Therefore, the results reported in Table 7 are the maximum single way distances for a sustainable energy balance.

Table 7 - Maximum single way distance consider energy balance

km / load	Sustainable distance min	Sustainable distance max
Cattle manure (slurry)	184	335
Pig manure (slurry)	194	322
Horse manure	435	962
Chicken manure	888	2055
Food waste (households)	1225	2666

In a sustainable energy view, it would be possible to make a transport radius for cattle manure, with low gas potential, 184 kilometers. For food waste, with low gas potential, it can be 1225 kilometers, transported with a single container truck, holding 15 ton. The trucks transporting food waste from Uddevalla have three containers and hold 35 tons. A study of this scenario, assuming low gas potential of the material and equally fuel consumption as the tank truck, still gives a long distance. The calculation shows that a food transport, like the one from Uddevalla, can be driven 1570 kilometers even for food waste with low gas potential, and still maintain a positive energy balance. This means that the energy balance allows an equal truck, from Sobacken, to run back and forth to Kiruna just to collect 35 ton food waste.

Impact of transport distance on financial balance

The energy balance, reported in Table 7, declares that relatively long transport distances are possible. However, in the Theory-chapter about cattle manure it was mentioned that financial viability is difficult to maintain. Table 8 contains data about the transportation from a co-digestion facility in Vårgårda, handling mainly cattle manure. More information about the facility in Vårgårda and the data related to it can be found in Appendix 1. The data will be used when calculating the financial balance. At the end of this section is a comparison with transportation data from another reference. Table 8 also contains additional data to calculate the total cost to produce biogas. The cost for electricity is the mean electricity price 2015-2020 and the cost for process heat is the customer price for district heating in Borås.

Table 8 - Data about transportation of cattle slurry and costs related to the process

	Data	Source
Transported slurry with tank truck	78 000 ton/year	(Åke Ljungström, 2021-05-11)
Total driven distance with tank truck	70 000 km/year	(Åke Ljungström, 2021-05-11)
Mean distance (single way)	15 km/load	(Åke Ljungström, 2021-05-11)
Truck driver working hours	12 hours/day	(Åke Ljungström, 2021-05-11)
Wear cost for tank truck	6 500 SEK/month	(Åke Ljungström, 2021-05-11)
Depreciation of tank truck	420 000 SEK/year	(Åke Ljungström, 2021-05-11)
Diesel price	16 SEK/litre	(OKQ8, 2021-05-08)
Bio-methane price	20 SEK/kg bio-meth.	(OKQ8, 2021-05-08)
Cost for process heat	0.54 SEK/kwh	(Borås Energi och Miljö, 2021)
Cost for electricity	0.39 SEK/kwh	(Energimyndigheten, 2021)
Cost for truck driver inc. taxes	32000 SEK/month	(Lönestatestik, 2021-05-08, Skatteverket, 2021-05-08)
Working hours in a year	2080 hour/year	(Tillväxtverket, 2021-08-05)

With the result from earlier calculations and data from Table 2, Table 6 and Table 8, the value per load is calculated.

$$\left(\frac{kWh\ CH_4}{ton\ WW} - \frac{kWh\ leak.}{ton\ WW}\right) * \frac{ton\ WW}{load} * \left(\frac{SEK}{kg\ Bio.m.} \middle/ \frac{kWh\ CH_4}{kg\ Bio.m.}\right) = \frac{SEK\ CH_4}{load}$$

Even the calculation of process costs per load is calculated with answers from earlier results and data from Table 6 and Table 8.

$$\left(\frac{SEK}{kWh\,pr.heat} * \frac{kWh\,pr.heat}{ton\,WW} + \frac{SEK}{kWh\,pr.el.} * \frac{kWh\,pr.el}{ton\,WW}\right) * \frac{ton\,WW}{load} = \frac{SEK\,proc.}{load}$$

To make further use of the data from Table 8 some conversions are necessary, to make the units similar. The transformations are demonstrated in Appendix 5 and the values are reported in Table 9.

Table 9 - Conversions of data from Table 8

	Calculations
Mean speed divided over a day	22 km/h
Transportation time	1.34 h/load
Depreciation of truck	6.00 SEK/km
Wear cost for the truck	1.11 SEK/km
Cost for truck driver	8.23 SEK/km
Diesel cost tank truck (slurry)	10.40 SEK/km
Diesel cost container truck (solid)	5.71 SEK/km
Total cost tank truck (slurry)	25.74 SEK/km
Total cost container truck (solid)	21.06 SEK/km

With the two previous cost related calculations and the cost related to loading, the financially feasible distances are calculated. The distance is again reported as single way distance to the collecting places.

$$\frac{\frac{SEK\,CH_4}{load} - \frac{SEK\,process}{load} - \frac{SEK\,loading}{load}}{\frac{SEK\,truck}{km} * 2} = \frac{single\,dist.}{load}$$

In Table 10 the calculated distances are reported.

Table 10 - Financially feasible single way distance

km / load	Economically distance min	Economically distance max
Cattle manure (slurry)	97	157
Pig manure (slurry)	101	152
Horse manure	121	260
Chicken manure	241	549
Food waste (households)	330	711

Note however, in the cost related calculations above there are some expenses which are not accounted for. For example, the expenses related to the workers at the facility are not included. Neither are service costs, nor the expenses of future investments. To cover these costs, and even to generate some yield, 50% of the income from the sold bio-methane is assumed to be spent. In the calculations below this 50% of the income is mentioned overhead cost.

$$50\% * \frac{SEK\,CH_4}{load} = \frac{SEK\,overhead}{load}$$

To calculate the financially feasible distances with a required overhead percentage of 50%, the same equation is used again but now even considering the overhead cost.

$$\frac{\frac{SEK\ CH_4}{load} - \frac{SEK\ process}{load} - \frac{SEK\ loading}{load} - \frac{SEK\ overhead}{load}}{\frac{SEK\ truck}{km} * 2} = \frac{single\ dist.}{load}$$

The calculated financially feasible distances are presented in Table 11.

Table 11 - Financially feasible single way distance, with 50% overhead percentage

km / load	Economically distance min	Economically distance max
Cattle manure (slurry)	48	79
Pig manure (slurry)	50	76
Horse manure	60	130
Chicken manure	120	275
Food waste (households)	165	355

A short analysis of the last two equations and the reported distances in Table 11, shows that the transport distances correlate with the required overhead cost. A required overhead percentage of 50% halved the transport distances. An overhead percentage of 70% would require transport distances equal to 30% of the distances reported in Table 10. It can also be seen from the other way, when distances get shorter, the overhead cost can be higher.

To validate the calculated distances in Table 10, some data in Table 6 and Table 8 is changed. The data is changed into values from a second reference, reported in Table 12. When using data from Table 12, the loading and unloading energy uses are not included in the energy usage for the tank truck. Instead, both the loading and unloading require diesel energy counted per ton wet weight, in the same way as for the container truck.

Table 12 - Data from a second reference

	Data	Source
Transported weight (slurry)	35 ton WW/load	(Tufvesson L., 2013, p.67)
Energy usage tank truck (slurry)	5.0 kWh/km	(Tufvesson L., 2013, p.67)
Loading/unloading energy	0.5 kWh/ton WW	(Tufvesson L., 2013, p.67)

When the values given from the co-digestion facility in Vårgårda are replaced with the values from Table 12, the tolerated distances become approximately 17% longer in Table 10 than in Table 11. This means that the calculated distances, reported in Table 10 and Table 11, may be shorter than necessary. However, at Hagelsrums farm they argue that the financial balance is hard to close for their 42 kilometres long transport of cattle slurry (Tom Birgersson, 2021-04-10). This corresponds relatively well with the calculated distance for cattle manure, with low gas potential, in Table 11.

Validation of the results

There is some margin of errors in the calculations above, mainly because the data is from many references. If the data would have been received from solely one anaerobic digestion facility, the result could be more valid at least for that type of facility. Unfortunately, there are several types of facilities and it is tough to make a general calculation which fits all of them. Some facilities consume more electricity, some more process heat and others have higher fuel consumptions. Maybe the largest difference between facilities is the number of workers and the need for services on the facility. Every additional worker result in a cost which reduces the financially feasible transport distance. A facility which requires fewer workers and services can transport material across longer distances.

As mentioned earlier in the calculation section, the data are related to mesophile digestion temperature of 37°C with batchwise hygienization at 70°C for one hour. A thermophile digestion process, like the one at Sobacken, probably has a different energy use. Moreover, the handling of solid waste on the site, including the process of making slurry in the pulper, is not included in the calculations. The used data is from processes which receive the slurry, not the solid waste materials.

The market value of the material

One important aspect to consider is the actual transport cost related to the organic materials presented in Table 10. For the results in the tables above it is assumed that the materials are free to collect or borrow. This is often the situation for pig or cattle slurry, the manure is free to borrow from the farmers, if they get the same volume back. Therefore, the facility needs to pay all costs for the transportation.

For horse farms the situation is different. They often need to pay to get rid of the manure. So, if the cost of sending the horse manure into biogas production is lower than the alternative handling, horse farms are probably willing to pay. For food waste, the situation is similar. The food producers usually need to pay to get rid of their food waste.

A special case is the handling of chicken manure. As the theory tells in the previous chapter, chicken manure is sold either as fertilizer or to biogas facilities. The assumed costs in the calculations are too low for chicken manure, because the manure is assumed to be free, and that is not true in reality.

Calculations implemented on the map

To provide a picture of what the calculated transport distances mean in relation to Sobacken, the map with the marked farms is used. In Figure 10 the same map as before is used, but now marked with transport distances of 20, 30, and 40 kilometres. The marked distances are marked along the bigger roads, so a farm within the 20km-area can possibly have a longer distance than 20 kilometres if the transport includes many curvy roads.

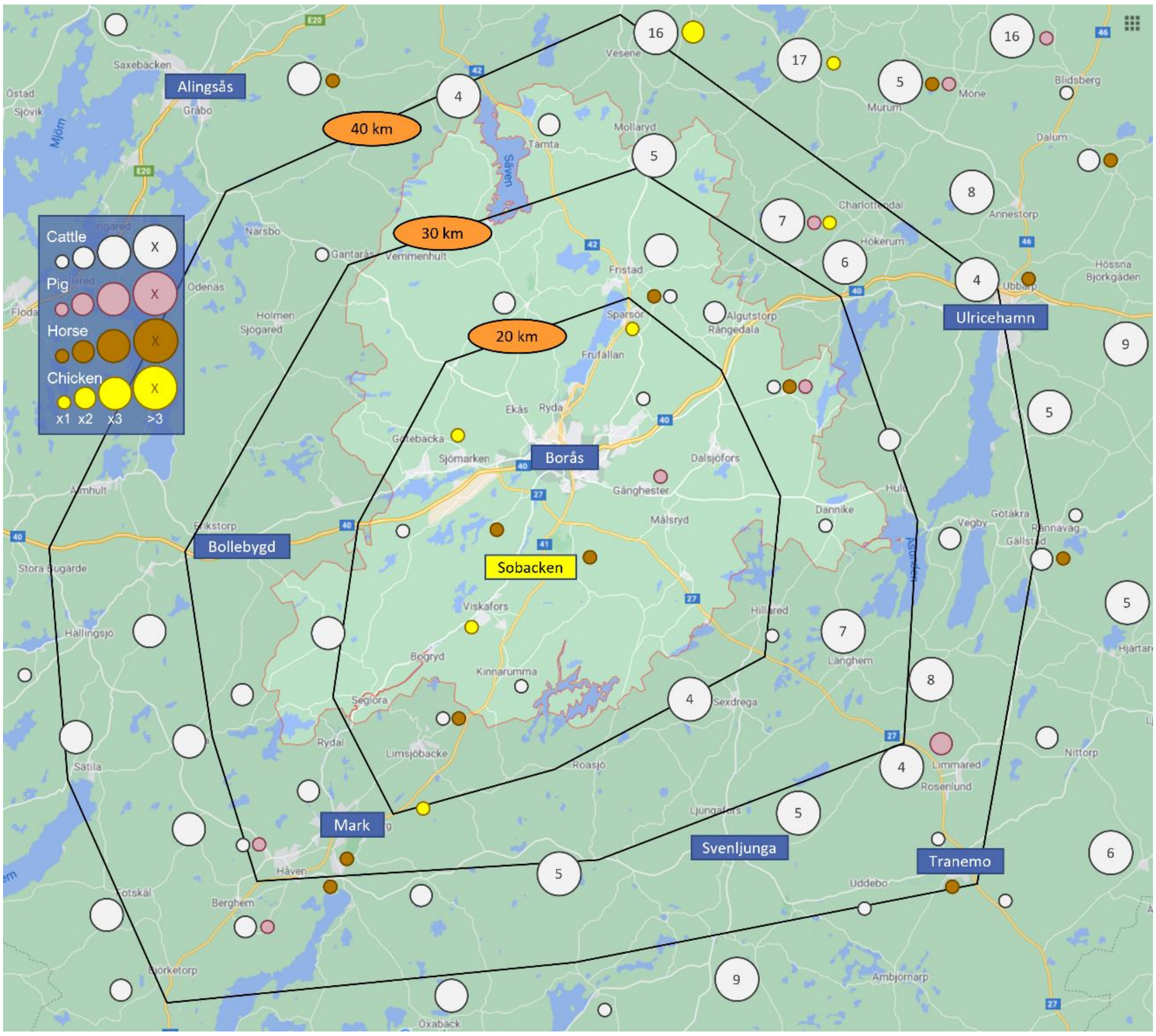

Figure 10 - A map with location of farms and marked transport distances

A study of the map in Figure 10 gives that more than 30 cattle farms are closer than 30 kilometres. Unfortunately, the map does not make a difference between farms producing solid manure or slurry. In the section "Introduction to the most common organic wastes" it clarifies that 70% of milk cows, and 40% of other cattle, producing slurry, therefore assume 55% of cattle farms producing slurry. This means about 17 cattle farms producing slurry closer than 30 kilometres from Sobacken. Additionally, there are three pig farms closer than 30 kilometres.

In the co-digestion plant in Vårgårda they mainly handle cattle slurry. To run their anaerobic digestion plants with approximately 11 000 cubic meters digester volume, they transport slurry from a bit more than 20 farms and receive some other waste materials (Åke Ljungström, 2021-05-11). At Sobacken, the digester volume will increase from 3000 into 6000 cubic meters. The need for additional material is relatively small when compared to the use of material in Vårgårda. This comparison clarifies that the 20 closest farms, closer than 30 kilometres, will be enough.

In addition to cattle and pig slurry there is horse manure in the area which can be used for biogas production. From the calculations of financially viable distances, reported in Table 10 and Table 11, the possible distance is very long. Moreover, the horse farms can be willing to pay the transportation costs and the yield will then be even bigger for the facility. For food waste, the situation is the same. Unfortunately, if the anaerobic digestion facility receives waste materials which the producers do not want back, it will be a cost for the facility to get rid of the extra digestate. Receiving cattle and pig manure, which the farmers want back after the process, is not related to a higher cost for digestate because the manure is only borrowed.

Chicken manure can be transported longer than the other three types of manure. This means that it definitely is financially viable to collect free manure from all chicken farms on the map. However, if the chicken farms want to get paid for the manure, the viable transport distance will be shorter.

DISCUSSION

Due to the decrease of emitted CO_2-equivalent greenhouse gases, the process results in a smaller footprint on the planet. The focus should be collecting manure slurry in the closest surroundings of Sobacken to make the most profit. But from a sustainable point of view, it is worth driving longer distances to give all farms the possibility to make biogas out of their manure. In the north-east area of Borås there are several cattle farms and from an environmentally sustainable point of view, a local anaerobic digestion facility could benefit to be placed there. This is not a responsibility for "Borås Energi och Miljö" but it is a misuse of resources and a profitable way of improving greenhouse gas emissions in the region. The region south of Borås is not as dense with farms as in the north-east. Therefore, the facility at Sobacken better focuses on the south region if they want to expand further.

A question is whether it is worth investing in a tank truck to transport slurry or if this service better is bought by a contractor. In Table 9 the mean time for a load is set to be 1.34 hours and values from Table 8 results in 173 working hours per month. Together with a rough assumption that 32,5 ton slurry is equal 20 cubic meters, this gives that one truck driver can collect 2600 cubic meters in a month, working 8 hours a day.

$$\frac{Monthly\ working\ hours}{Time\ per\ load} * Cubic\ meters\ per\ load = \frac{173}{1.34} * 20 \approx 2600$$

Due to the reconstruction of the facility at Sobacken, the digester volume increases with 3000 cubic meters, the hydraulic retention is assumed to still be 30 days. The rough calculation shows that it can be worth investing in a tank truck and one employment for a truck driver. It is not necessary to collect 3000 cubic meters of slurry if horse manure and extra food waste also is collected.

Sobacken has a special possibility to handle solid waste due to its focus on handling food waste. This possibility is unusual at co-digestion facilities and is worth making use of. Therefore, a focus in collecting horse manure and more food waste can be advocated. But these materials alone are not enough to fill the extra 3000 cubic meters digester volume. The slurry from cattle and pig manure is needed to completely fill this digester volume. Moreover, the manure slurry should be used to decrease the need for water in the pulper.

As the Analysis-chapter shows, there are several chicken farms in the surrounding region of Sobacken. Due to the extra cost for chicken manure, compared to other manure types, it is better to focus on other waste materials in the region. If it becomes a shortage of material in the surrounding region in the future, it can be worth buying some chicken manure from farms. However, without chicken manure from cage chickens it may be possible to KRAV-certify the facility and sell biofertilizer to KRAV-certified farmers. But to make this possible, some changes of the existing process are probably required.

In this report it has been assumed that the trucks used for collection of manure are fueled by diesel. This is mainly because diesel is the most common fuel to use for manure transports today. But in later years it has become more common with trucks fueled by bio-methane or liquid bio-methane. A truck fueled by bio-methane is consuming approximately the same energy, so the calculations in the Analysis-chapter are still valid. To make the biogas production even more independent from fossil energy, the trucks for manure transportation to Sobacken are advocated to be bio-methane fueled.

The map of farms in the surroundings of Borås shows a big biogas potential in the region. Using manure from the nearest farms to fill the increased digester volume is a good start. But unfortunately, it will probably not be possible to receive manure from all farms in the region without lack of digester volume. In the future, if the interest for anaerobic digestion of manure is high, an expansion of the facility to fill the request needs to be discussed. Making use of the manure in the surroundings is a profitable way to decrease the emissions of greenhouse gases and to produce fossil free energy. To expand an existing facility is both cheaper and probably more sustainable than building a new one.

CONCLUSION

The location of Sobacken, south of Borås, makes manure from animals interesting for the increase of biogas production. Even a continued and developed system to collect food waste is worth working on due to the high gas yield of food waste. Solid waste, such as horse manure, can be received with the existing technique. But to make it possible to receive larger quantities of manure slurry, new technologies are required.

There is a large percentage of cattle farms in the region and the environmental benefits of producing biogas from the cattle manure is high. The economic analysis and the map of farms in the region showed that the calculated transport distance is long enough to cover the need for extra material at Sobacken. The number of pig farms in the region is low but they are located close to Sobacken. The analysis of transport distance for pig manure is similar to the distance for cattle manure. However, for cattle manure some transportations can be made without financial sustainability, the societal benefit of lowering methane emissions can make it worthwhile. If the manure slurry can replace some water needed in the slurry making process of solid waste, it is even more worthwhile to collect it.

Horse manure and food waste can be transported way longer than slurry of pig and cattle manure. Due to the uncommon technology at Sobacken, to receive and handle solid materials, horse manure and food waste are ought to be focused on. Some important prerequisites for the received horse manure are that the used bedding material is straw pellets and that the manure is collected only inside the stable. Chicken manure has high gas potential and there are several chicken farms in the surroundings of Sobacken. Unfortunately, the price for chicken manure can inhibit the motivation to receive it.

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APPENDIX

Appendix 1

Study visits and interviews (in Swedish)

During the working process with this thesis some interviews and study visits has been implemented. The knowledge shared by these people are summarized in this Appendix. The summaries are written in Swedish.

Robert Kjellstrand, 2021-02-03

Studiebesök, Sobacken

Borås energi och Miljö är ett kommunalt bolag. Det gör att det inte främst är ett vinstdrivande bolag i samma bemärkelse som andra bolag utan har som uppgift att serva kommunens invånare.

I dagsläget finns det en mottagningshall för flytande material på anläggningen. Tekniken bygger på att slurryn pumpas ur lastbilen in i bufferttanken, vilket gör att pumpproblem hämmar lossning av flytande material. I anslutning till mottagningshallen för flytande material finns en hygieniseringsanläggning som kan röta material batch-vis vid 70°C. Men idag hygieniseras allt material istället under den termofila rötningprocessen i rötkammaren.

Det byggs en ny mottagningsprocess för fast avfall som ska testas i maj och driftsättas i juni (2021). Den nya mottagningen använder Grubbens HC-Pulper för att omvandla det fasta avfallet till slurry. Tekniken i pulpern bygger på att snabb rotation av vätskan slår sönder mjukt material. Det är samma teknik som används inom massaindustri. Cirka 80-85% av inkommande matavfall förväntas nå rötkammaren med nya systemet. I dagens mottagningsprocess är motsvarande procentsats 50%. Den nya anläggningen släpper dock igenom mer fibrer och utrötningsgraden blir då lägre. Men implementeringen av efterrötningskammaren kommer att öka utrötningsgraden och den förväntas därför stanna kvar på nuvarande, cirka 80%. Problemet som finns i dagens anläggning, med att plast och annat icke organiskt avfall följer med i slurryn, hoppas minska avsevärt med den nya tekniken.

Med den nuvarande tekniken produceras cirka 10-15GWh. Efter ombyggnationen förväntas anläggningen producera cirka 30GWh biogas och Borås Energi & Miljö kommer då sälja rågas till ett externt bolag istället för att själva uppgradera gasen till fordonsgas. En stor andel av de fordon som används för avfallshantering inom Borås Energi & Miljö idag drivs av egen fordonsgas.

Idag tas matavfall från hushåll in från Borås, Ulricehamn, Mark, Bollebygd samt Uddevalla med kranskommuner. I Borås kommer ett nytt källsorteringssystem att införas i samband med idrifttagandet av den nya mottagningshallen och den gamla anläggningen kommer att avvecklas. Mark och Bollebygd har idag ett separat kärl för matavfall likt det system som Borås kommun är på väg att införa. Ulricehamn har nyligen infört ”svarta och vita påsar”, det system som inom kort kommer avvecklas i Borås. Uddevalla har ingått avtal att leverera 5000 ton rent matavfall om året till Sobacken.

Avloppsslam och fett från fettavskiljare, bl.a. från restauranger, rötas i en helt separat anläggning. Anläggningarna binds samman först i ett gasnät och använder därför samma gasklocka.

Den rötade slurry pumpas ut till rötrestlagret utan någon nedkylning. Nedkylning har tidigare praktiserats men har avbrutits på grund av problem med beläggningar som bildas i värmeväxlaren. Efter ombyggnationen av anläggningen kommer den rötade slurryn fortsatt pumpas till rötrestlagret utan nedkylning. Detta är i alla fall planen för den närmaste framtiden.

Hästgödsel och djurparksgödsel är svårt att hantera med dagens anläggning (innan ombyggnationen 2021). Dessa gödselsorter innehåller dessutom höga halter halm som försvårar hanteringen i en biogasprocess. Dock finns det en önskan från hästgårdar samt djurparken att Sobacken ska kunna göra någon form av energiåtervinning av deras gödsel.

På området finns det en gammal vattenreservoar som använts som buffert för återvunnen vätska från processen. I reservoaren blandades färskvatten in i den återvunna vätskan för att göra den möjlig att använda i processen igen. Vätskan användes för att producera slurry av hushållsavfallet.

Robert Kjellstrand, 2021-04-29

Handledarmöte med Robert Kjellstrand

För att omvandla matavfall och andra fasta fraktioner till en slurry blandas de med vatten i pulpern. Flytgödsel kan i viss utsträckning ersätta vatten i denna process, dock inte allt. Om flytgödsel ersätter lite av vattnet som tillförts processen blir också andelen vatten i den slutliga rötresten mindre. När andelen vatten i rötresten är sänkt, och dessutom ersatt med flytgödsel, så kommer näringsvärdet i rötresten att vara högre. Att ersätta en viss mängd vatten med flytgödsel innebär ett mervärde för flytgödseln.

Jesper Englund, 2021-03-26

Studiebesök, Limmareds Säteri, Limmared, Tranemo kommun

Jesper Englund driver en gård med 200-250 nötdjur för köttproduktion samt cirka 400 svin. Tjurarna går på spalt och gödseln skrapas ut med automatik till en flytgödselbrunn, här används alltså inget strömedel. Vid kalvning går kor och kalvar på ströbädd, men detta är en liten del av verksamheten så det bildas inga stora kvantiteter med fastgödsel från bäddarna.

Från svinstallet transporteras också flytgödsel ut med automatik till en gödselbrunn. Nötflytgödseln och svinflytgödseln är separerad i två olika brunnar på grund av dess olika egenskaper. Nötflytgödseln har högre kvävehalt och svingödseln högre fosforhalt därmed lämpar de sig olika bra på olika grödor och vid olika tider på säsongen. Dessutom sedimenterar svinflytgödseln mer än nötflytgödseln och kräver mer omblandning under spridningsperioden.

På gården har det nyligen byggts en ny gödselbrunn för nötflytgödseln. Den är inte byggd på det vanliga viset, med betong, utan består av en tjock presenning som ligger i en grop. Den kan alltså liknas vid en konstgjord damm. Anledningen till att Jesper valt att investera i denna sorts gödselbrunn är den ekonomiska fördelen. Dock är presenningen känslig för att bli skrapad med t.ex. gödselomröraren. Men enligt Jesper ska livslängden vara i princip den samma som för en gödselbrunn i betong, så länge ingen allvarlig tillstötning i presenningen sker.

Henrik Strömbom, 2021-03-30

Studiebesök, Eskilsryd, Brämhult, Borås kommun

Strax öster om Borås tätort ligger Eskilsryd, en gård som föder upp stutar (kastrerade tjurar). Gården har cirka 300 stutar och drivs av Henrik och Per-Johan Strömbom. Gården är KRAV-märkt och behöver därför följa vissa bestämmelser gällande djurhållningen. Stutarna måste gå ute 5 månader av deras tvååriga liv och därför är stallen tomma under sommaren. I stallen måste stutarna ha en bädd att gå och leva på. Endast närmast foderbordet finns en skrapgång, utan bäddmaterial, som töms dagligen. Henrik berättar att bädden strös med ny halm varje dag och att denna grävs ut två gånger per år. Under ett år töms stallen på totalt ~1500 kbm bäddmaterial som efter att ha brunnit i hög under några månader gödslas ut som fastgödsel på åkrarna. För att halmen som finns i bäddmaterialet ska gå att bryta ned på åkern är det viktigt att materialet får bränna ett tag innan gödsling, dessutom behöver gödselspridaren finfördela materialet och riva isär halmen. Gödseln från skrapgångarna läggs på en betongplatta och sprids för sig som kletgödsel, men med samma gödselspridare som sprider bäddmaterialet.

Thomas Sylvesson, 2021-04-01

Telefonintervju, Sylves lantbruk, Brålanda-Mellerud, Dalsland

Mellan Brålanda och Mellerud ligger ett flertal gårdar med egna biogasanläggningar som har investerat i en gemensam uppgraderingsanläggning dit de pumpar sin rågs genom pipelines. Thomas Sylvesson driver en av gårdsanläggningarna och han rötar huvudsakligen svingödsel från sitt eget svinstall. Men redan när anläggningen byggdes insåg Thomas vikten av ett varierat substrat att mata in i rötkammaren och byggde därför anläggningen tillräckligt stor för att kunna ta emot ytterligare substrat. Två dagar i veckan körs nötflytgödsel till anläggningen från gårdar inom några kilometers avstånd. Dessutom tar Thomas emot slakteriavfall som han blandar med nöt och svingödseln. Thomas själv skulle aldrig välja att röta enbart svingödsel, utan menar att gasutbytet blir högre när det samrötas med nötgödsel. Dessutom är en anaerob nedbrytningsprocess svår att starta med enbart svingödsel, trots att en dos ympsubstrat tillförs, detta problem har omkringliggande anläggningar råkat ut för. Svingödsel genererar mer biogas än nötgödsel, men en samrötning av dem tillsammans genererar mer biogas än vad enbart svingödsel gör.

En samrötad gödsel som innehåller både svin och nötgödsel får en bättre blandning av fosfor och kväve, nötgödsel har ett överskott med kväve och svingödsel ett överskott av fosfor. Av denna anledning så kompletterar de två substraten varandra bra även efter rötningsprocessen. Thomas ser inte att svingödsel bidrar till sedimentering i rötkammaren trots att den sedimenterar snabbare än nötgödsel. Den effektiva omrörningen tillåter inte substraten att sedimentera. Sedimentering är inte heller något problem för rötresten i lastbilens tank under transport.

Thomas menar att det krävts en liten omställning för de bönder som levererar gödsel till hans anläggning, de måste se till att gödseln är omrörd innan lastbilen kommer och hämtar samt att de måste investera i en brunn för att ta emot biogödsel. Normalt sett rör bönder endast om i gödselbrunnen innan utgödsling. Thomas säger att han inte anser det lönsamt att köra gödseln längre än 10-20km, men han säger också att det beror helt och hållet på hur hög torrsubstans (TS) som finns i gödseln. En gödsel med hög torrsubstans kan vara värd att hämta på längre avstånd. Han menar att mängden tvättvatten som används för djuren och stallet har en betydande påverkan på torrsubstansen. För att höja torrsubstansen i sin egen process blandar Thomas in finfördelat bäddmaterial från sina svinstall men han säger också att det händer att det blir för mycket bäddmaterial i rötkammaren och att det då bildas ett svämtäcke på toppen. För att kunna blanda in mer bäddmaterial utan att det bildas ett svämtäcke hade en toppmonterad omrörare varit att föredra, i nuläget sitter omrörarna monterade i väggarna.

Anette Carr, 2021-04-02

Telefonintervju, Främgärde, Brämhult, Borås kommun

Anette har en liten hästgård i Brämhult, Borås, och har börjat strö med halmpellets i sina boxar. Anledningen till att hon började använda halmpellets var att hon då kunde skänka sin gödsel till en gård med nötdjur i närheten. När hon tidigare strödde i boxarna med sågspån ville de omkringliggande gårdarna inte ta emot gödseln av rädsla för terpener som förgiftar marken. Därför var Anette tidigare tvungen att betala Borås Energi och Miljö en mottagningsavgift för att de skulle ta hand om gödseln från stallet. Efter beräkningar visade det sig att det mest ekonomiska vara att köpa in halmpellets, som är dyrare än sågspån, men att då kunna lämna ifrån sig gödseln utan att betala mottagningsavgiften. Utöver den ekonomiska vinningen så är det ett bra strömedel. Det är enkelt att använda och det ger ett rent intryck i boxarna.

Andreas Markusson, 2021-04-05

Studiebesök, Götestorp Gård, Vesene, Herrljunga kommun

Götestorps gård installerade en egen biogasanläggning på gården för några år sedan. De har cirka 1000 kreatur totalt, varav 350 är mjölkkor. Biogasen som produceras förbränns i en ottomotor som genererar el. Majoriteten av tiden går generatorn på sin fulla effekt och genererar 100kw el. Andreas menar att det i princip endast är den elen som förbrukas på gården som är ekonomiskt lönsam att producera. Den el som säljs och skickas ut på elnätet ger dåligt betalt. Det är alltså storleken på gårdens egna elbehov som avgör om det är lönsamt att producera el av gödseln. En förbränningsmotor producerar även värme som måste kylas bort, i detta fall ca 200kw. Värmen används i dagsläget inte i någon större utsträckning mer än för att värma rötkammaren, men planer på att förbruka överskottsvärmen finns för framtiden.

Rötningen sker i en 1500 kbm stor rötkammare med en toppmonterad omrörare. Med den toppmonterade omröraren uppstår inga stora problem med svämtäckesbildning så Andreas blandar in allt gårdens bäddmaterial i rötningsprocessen. Dock är djurhållning på ett sådant sätt att det inte bildas så mycket bäddmaterial utan mest flytgödsel. Bäddmaterialet matas in i en foderblandare som sliter isär halmen, sedan skruvas materialet in till förbrunnen där det blandas med flytgödseln. Från förbrunnen pumpas materialet genom en kvarn som sönderdelar halm och annat material ytterligare innan det matas in i rötkammaren. Rötningen sker i mesofil temperatur och det är endast nötgödsel från den egna gården som rötas i anläggningen så hygienisering är inte nödvändig. Det finns dock möjlighet att höja temperaturen till termofil rötning och därmed hygenisera substratet inuti rötkammaren. Detta för att i framtiden kunna ta in ytterligare substrat, men då måste elpriset vara högre så att det är värt att producera mer el än vad gården förbrukar.

De fördelaktiga egenskaperna som biogödseln ska få, jämfört med vanlig gödsel, ser Andreas endast som en bonus. Att biogödseln inte avger någon stark lukt vid spridning har han redan märkt. Men den enda fördelen med det är att grannar inte störs av lukten och att han därmed kan sprida gödsel även på kvällar när grannarna sitter och grillar på altanen. Att användningen av mineralgödsel kommer att minska har Andreas ingen större förhoppning om, men om det blir fallet är det en positiv effekt menar han.

Tom Birgersson, 2021-04-10

Studiebesök, Hagelsrums Gård, Målilla, Småland

Utanför Målilla i Småland har familjen Birgersson en biogasanläggning som de satte i bruk i slutet av 00-talet. Då rötade de endast gödseln från den egna gården och använde den för att producera el. Dessvärre sjönk elpriserna kraftigt under de första åren som anläggningen var i drift och det var svårt att få lönsamhet i anläggningen. I slutet av 10-talet investerade de därför i en till större rötkammare och en uppgraderingsanläggning. Den gamla rötkammaren används nu som en efterrötkammare. Med en större rötkammarvolym finns också möjligheten att ta emot mer substrat. Birgerssons egen gård har expanderat och håller idag 650 mjölkkor samt några hundra kvigor och tjurar. Dessutom hämtas flytgödsel från två andra gårdar i området med lastbil. En gård ligger på 2 mils avstånd och den andra på 4,2 mils avstånd, enligt Tom är det knappt lönsamt att hämta gödsel från gården längst bort. Eftersom det endast är gödsel från totalt tre gårdar krävs inte någon hygienisering. Fastgödsel från Birgerssons egen gård matas in i processen, men inte från de andra gårdarna.

För att uppgradera gasen till fordonsgas används membranteknik och den uppgraderade gasen pumpas i en 5km lång pipeline till en tankstation inne i Målilla. Vid tankstationen fylls även lastväxlarflak som körs till 3 andra stationer i närliggande samhällen. Tom menar att en viktig anledning till att de vågat investera i den nya anläggningen är möjligheten att sälja fordonsgas till länstrafiken i Kalmarregionen. Att endast sälja till den privata marknaden kändes för osäkert vid uppstarten, men i nuläget verkar det som att den privata marknaden hade varit tillräcklig för att få lönsamhet i investeringen. Tom tror att förvätskning av fordonsgas är något för framtiden eftersom den då kan transporteras mer ekonomiskt än idag. Att generera el av biogasen tror inte Tom kommer att vara effektivt nog, det kommer alltid vara svårt att få bra lönsamhet i en sådan process.

Gällande möjligheten att ersätta mineralgödsel med den producerad biogödseln, menar Tom att de inte setts någon märkbar effekt. De använder fortfarande mineralgödsel på grödorna för att lyckas förse grödan med tillräcklig mängd kväve. Utan mineralgödsel skulle den befintliga åkermarken inte räcka till för den mängd djur de har på gården. Huruvida biogödseln som de producerar gjort att de använder mindre konstgödsel på åkermarken är dock svårt att avgöra eftersom gårdens antal djur kontinuerligt expanderat i takt med att biogasprocessen har tagits i bruk. Tom vågar varken fördöma eller dementera att den ökade halten ammoniumkväve i gödseln har ökat mängden producerat foder, på motsvarande areal.

Bengt Berggren, 2021-04-26

Telefonintervju, Sjömarkens Hönsgård, Sjömarken, Borås

På Sjömarkens hönsgård finns det bara värphöns och alla hönsen går inomhus. De har både stallinredningar för burhöns och för frigående höns. Från de höns som sitter i burar matas det ute en ren gödselfraktion, utan bäddmaterial, på mattor som rullar under burarna. De frigående hönsen har tillgång till både en golvyta med bädd och en upphöjd sittyta på nät, med gödselsmattor under. Med mattor transporteras en ren gödselfraktion ut även från stallet med frigående höns. Delar av bädden skrapas kontinuerligt med ett automatiserat system, den resterande bädden är porös och består till stor del av torkad, söndersmulad avföring och en försumbar del strömaterial. På grund av detta består även materialet som skrapas ut från bädden nästan uteslutande av hönsspillning. Detta innebär att gödseln som produceras på Sjömarkens hönsgård innehåller näst intill 100% djurspillning.

Gödseln säljs idag till en extern aktör som i sin tur säljer hönsgödseln till lantbrukare som behöver en fosfor-rik gödsel. Det gör att gården får betalt för gödseln de producerar. Gödseln hämtas kontinuerligt under sommarhalvåret från gården med lastbil och lastas av de anställda på hönsgården. På vintern används lastmaskinen till snöröjningsuppdrag och kan då inte vara behjälplig för lastning av gödsel. Administrationen av gödselförsäljningen som det externa företaget sköter är de nöjda med. Bengt berättar att gödseln tidigare har sålts till en biogasanläggning, men att biogasföretaget bröt avtalet efter att de börjat få problem i rötningsanläggningen, förmodligen på grund av kalkavlagringar.

Kajsa Nilsson, 2021-05-06

Telefonintervju, MR Sjuhärad, Länghem, Tranemo kommun

MR Sjuhärad är idag upphandlade till att distribuera all biogödsel från rötningsanläggningen på Sobacken. År 2020 transporterade de bort 26 000 ton biogödsel från biogödselbrunnen på Sobacken. Transporterna sker med tankbil och sköts av företaget Lundby Maskinstation. Biogödseln säljs som gödningsmedel till gårdar i närområdet, både till gårdar som odlar djurfoder och gårdar som odlar livsmedel. Vid användning av biogödseln till djurfoder blandas den ofta samman med gårdens egen stallgödsel. Eftersom biogödseln är lättflytande, men fortfarande har ett högt näringsvärde, bidrar den till att gödselblandningen blir mer lättflytande och ändå bibehåller ett minst lika bra näringsinnehåll.

Kajsa försöker sälja gödseln till odlare så nära Sobacken som det är möjligt för att minska transportkostnaderna och även utsläppen. Dock är detta svårt under vintertiden eftersom det är brist på stora gödselbrunnar i Boråsområdet. På vintern kan transportavståndet överstiga 70 km, enkel resa, men under växtsäsongen hålls transportsträckorna mellan 30-60 km. De transporter som överstiger 70 km går huvudsakligen till Vara, men också mot Gislaved, och står för 7000 respektive 1000 ton gödsel.

MR Sjuhärad distribuerar även biogödsel från en KRAV-märkt rötningsanläggning i Lidköping. Biogödseln från Lidköping kan de därför sälja till KRAV-odlare. I KRAV-odlingar kan biogödseln fungera som en ersättare till konstgödsel eftersom konstgödsel inte är tillåtet för KRAV-odlare. Dock ersätter biogödsel inte användandet av konstgödsel på konventionella gårdar i någon märkbar utsträckning. På konventionella odlingar används biogödseln endast som ersättning eller komplement till stallgödsel.

Åke Ljungström, 2021-05-11

Telefonintervju, VH Biogas, Vårgårda

Åke Ljungström jobbar som lastbilschaufför på VH Biogas, en samrötningsanläggning mellan Vårgårda och Herrljunga. Anläggningen rötar huvudsakligen flytgödsel från nötkreatur, utspridda på cirka 20-25 gårdar. Utöver nötgödsel samrötas även, svingödsel, hönsgödsel, slakterirester från höns, kasserad kattmat och kasserat torrfoder för hundar. Anläggningen har två huvudrötkammare med en gemensam rötningsvolym på 8700 kubikmeter, dessutom finns en efterrötningskammare på 2500 kubikmeter.

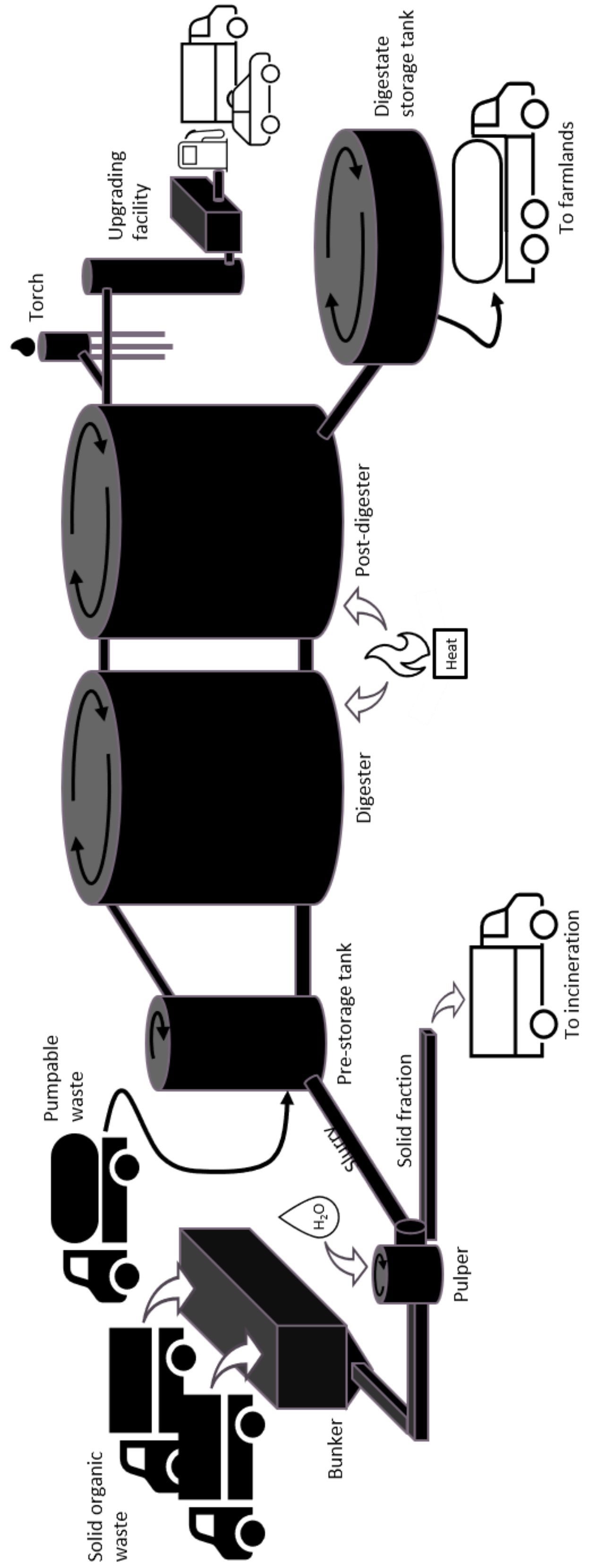
Majoriteten av transporterna sker med den egna draglastbilen av märket Volvo med en tanktrailer av märket VM Tarms. Lasten i tanken brukar uppgå till 32,5 ton och den genomsnittliga sträckan som gödseln transporteras är ca 10-15km. Andra substrat som hämtas körs ofta längre sträckor. De korta sträckorna som gödseln transporteras är i Vårgårdas närområde och därmed passeras flera korsningar för varje lass, därmed utsätts lastbilen för många starter och stopp. Den genomsnittliga förbrukningen av diesel, på 65 liter per 100km, blir därmed förhållandevis hög jämfört med en lastbil som körs i fjärrtrafik. Lastbilen körs ca 7 000 mil om året och bemannas i snitt 12 timmar per arbetsdag. Totalt transporter den egna lastbilen omkring 73 500 ton gödsel till anläggningen och 78 000 ton ut från anläggningen varje år.

För lastbilen är ett serviceavtal tecknat med Volvo som täcker alla kostnader för uppkomna skador samt service. Serviceavtalet, som kostar 6500 SEK per månad, är ett välinvesterat abonnemang för VH Biogas menar Åke. Han är förhållandevis säker på att underhållet av lastbilen hade blivit dyrare utan serviceabonnemanget. Detta därför att slitaget per mil är högt tack vare de korta transportsträckorna, dessutom går dessa transporter ofta på små krokiga vägar. Avskrivningen på lastbilen, inklusive tanktrailern, är 420 000 SEK per år.

Biogödseln som transporteras ut från anläggningen körs huvudsakligen tillbaka till de gårdar där gödseln är hämtad, gödseln lånas alltså bara av gårdarna. Dock gör volymen av andra mottagna substrat, så som kasserad kattmat, att mängden biogödsel blir större än den inkomna mängden gödsel. Några gårdar köper därför extra biogödsel och får då betala 15 eller 30 SEK per ton beroende på vinter- respektive sommarsäsong. Det billigare priset på vintern beror på efterfrågan och böndernas svårighet att ta emot gödseln under vintersäsongen (1 aug – 15 mars). De gårdar som köper biogödsel från VH Biogas är uteslutande ekologiska gårdar.

Appendix 2

Flow sheet of the anaerobic digestion facility at Sobacken



Appendix 3

C/N-ratio of the slurry at Sobacken

The data from the anaerobic digestion of out-sorted food waste at Sobacken are e-mailed from Robert Kjellstrand 2021-03-29

Month	TOC [% of TS]	Nitrogen [%]	TS [%]	Nitrogen [% of TS]	C/N-ratio [-]
dec-20	54,8	0,38	8,2	4,63	11,8
sep-20	49,6	0,57	10,4	5,48	9,0
jun-20	53	0,51	14,5	3,52	15,1
mar-20	57,7	0,47	17,8	2,64	21,9
dec-19	52,2	0,45	13,7	3,28	15,9
sep-19	48,1	0,48	13,5	3,56	13,5
jun-19	48,8	0,5	11,7	4,27	11,4
mar-19	51,2	0,41	12,1	3,39	15,1
dec-18	46,5	0,47	12,3	3,82	12,2
sep-18	53	0,48	11,7	4,10	12,9
jun-18	53,1	0,45	8,9	5,06	10,5
mar-18	49,4	0,42	9,4	4,47	11,1

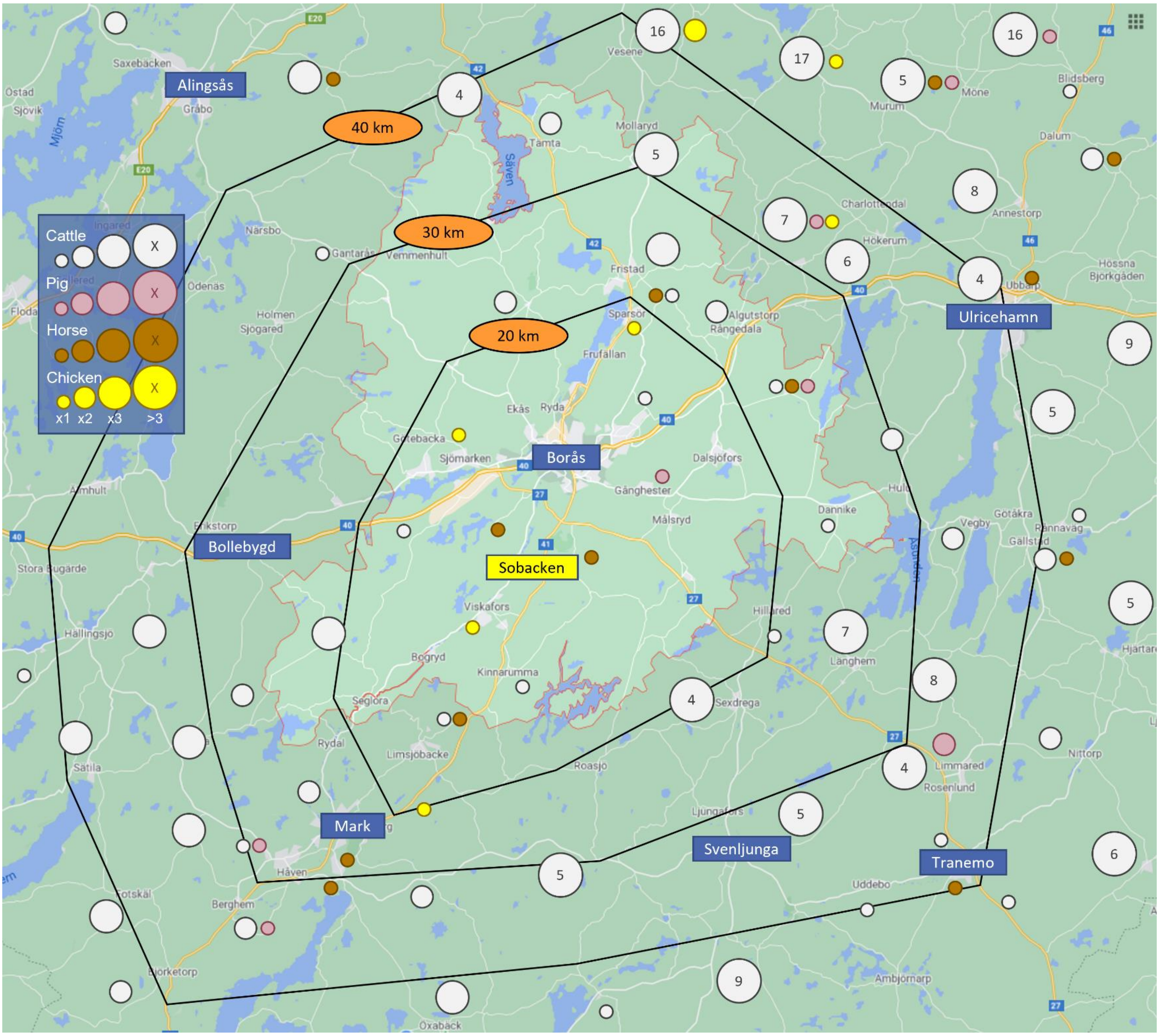
Appendix 4

Location of farms, data from Jordbruksverket 2021-04-26

In this Appendix the data sent from Jordbruksverket 2021-04-26 are reported. The data contains all farms in the area covered by the map below. The number of farms is counted for each post code and divided depending in type of animals. The data is reported in the table below.

Municipality	Postcode	Post office	Cattle	Horse	Chicken	Pig	Municipality	Postcode	Post office	Cattle	Horse	Chicken	Pig
Borås	51397	Borgstena	5				Svenljunga	51290	Hillared	1			
Borås	50493	Borås		1			Svenljunga	51264	Holsljunga	1			
Borås	50494	Borås	1				Svenljunga	51291	Sexdrega	4			
Borås	50495	Borås		1			Svenljunga	51292	Svenljunga	5			
Borås	50496	Bredared	2				Svenljunga	51293	Svenljunga	5			
Borås	50790	Brämhult	1				Svenljunga	51294	Svenljunga	9			
Borås	51694	Dannike	1				Tranemo	51461	Dalstorp	5			
Borås	51393	Fristad	2				Tranemo	51495	Grimsås	6			
Borås	51395	Fristad	1	1			Tranemo	51450	Limmared	4			2
Borås	51396	Fristad	3				Tranemo	51452	Länghem	7			
Borås	50771	Gånghester				1	Tranemo	51453	Månstad	8			
Borås	51592	Kinnarumma	1				Tranemo	51454	Nittorp	2			
Borås	51693	Rångedala	2				Tranemo	51432	Tranemo	1			
Borås	51593	Seglora	3				Tranemo	51434	Tranemo		1		
Borås	51891	Sjömarken			1		Tranemo	51491	Tranemo	1			
Borås	51350	Sparsör			1		Tranemo	51492	Uddebo	1			
Borås	51532	Viskafors			1		Ulricehamn	52376	Blidsberg	1			
Borås	51692	Äspered	1	1		1	Ulricehamn	52377	Blidsberg	16			1
Mark	43895	Hällingsjö	1				Ulricehamn	52375	Dalum	2	1		
Mark	51994	Björketorp	2				Ulricehamn	52360	Gällstad	2	1		
Mark	51996	Fotskäl	3				Ulricehamn	52361	Gällstad	1			
Mark	51173	Fritsla	1	1			Ulricehamn	52398	Hökerum	6			
Mark	51196	Berghem	2			1	Ulricehamn	52399	Hökerum	7		1	1
Mark	51197	Hajom	3				Ulricehamn	52393	Marbäck	5			
Mark	51168	Hyssna	3				Ulricehamn	52392	Timmele	8			
Mark	51198	Hyssna	2				Ulricehamn	52394	Tvärred	2			
Mark	51153	Kinna		1			Ulricehamn	52337	Ulricehamn		1		
Mark	51156	Kinna	2				Ulricehamn	52390	Ulricehamn	4			
Mark	51159	Kinna			1		Ulricehamn	52397	Ulricehamn	9			
Mark	43897	Rävlanda	3				Ulricehamn	52362	Vegby	2			
Mark	51191	Skene	1			1	Ulricehamn	52395	Älmestad	5	1		1
Mark	51174	Skephult					Herrljunga	52495	Ljung	16		2	
Mark	51199	Sätila	3				Herrljunga	52496	Ljung	17		1	
Mark	51131	Örby		1			Vårgårda	44794	Vårgårda	4			
Mark	51192	Örby	2				Alingsås	44191	Alingsås	2			
Mark	51195	Öxabäck	3				Alingsås	44193	Alingsås	3	1		
							Bollebygd	51794	Töllsjö	1			

On the map, white dots count cattle farms with more than 50 cattle and pink dots count pig farms with more than 50 pigs. Brown dots count horse farms with more than 10 horses and yellow dots count chicken farms with more than 500 chickens. The three smallest dots stand for one, two or three farms respectively, on that postcode. The biggest dot, the one with a number, stands for the number of farms given by the number.



Appendix 5

Conversion of data used in the Analysis

In the section "Calculation of transport distance" some of the simple equations are not shown. Instead, they are shown in this Appendix. Data from Table 13 and Table 14 are resulting in the values in Table 15.

Table 13 - Truck data (the same as Table 6)

	Data	Source
Transported weight (slurry)	32.5 ton WW/load	(Åke Ljungström, 2021-05-11)
Transported weight (solid)	15 ton WW/load	(Tufvesson L., 2013, p.67)
Energy usage tank truck (slurry)	0.65 litre diesel/km	(Åke Ljungström, 2021-05-11)
Diesel energy content	9.8 kWh/litre	(Energigas Sverige, 2021-05-08)
Energy usage container truck (solid)	3.5 kWh/km	(Tufvesson L., 2013, p.67)
Loading/unloading energy	0.5 kWh/ton WW	(Tufvesson L., 2013, p.67)

Table 14 contain data about the transportation from a co-digestion facility in Vårgårda, handling mainly cattle manure. More information about the facility in Vårgårda and the data related to that facility can be found in Appendix 1. Table 14 also contains additional data to calculate the total cost to produce biogas. The cost for electricity is a mean value of the electricity price in year 2015-2020 and the cost for process heat is the costumer price for district heating in Borås.

Table 14 - Data about transportation and costs related to the process (same as Table 8)

	Data	Source
Transported slurry with tank truck	78 000 ton/year	(Åke Ljungström, 2021-05-11)
Total driven distance with tank truck	70 000 km/year	(Åke Ljungström, 2021-05-11)
Mean distance (single way)	15 km/load	(Åke Ljungström, 2021-05-11)
Truck driver working hours	12 hours/day	(Åke Ljungström, 2021-05-11)
Wear cost for tank truck	6 500 SEK/month	(Åke Ljungström, 2021-05-11)
Depreciation of tank truck	420 000 SEK/year	(Åke Ljungström, 2021-05-11)
Diesel price	16 SEK/litre	(OKQ8, 2021-05-08)
Bio-methane price	20 SEK/kg bio-meth.	(OKQ8, 2021-05-08)
Cost for process heat	0.54 SEK/kWh	(Borås Energi och Miljö, 2021)
Cost for electricity	0.39 SEK/kWh	(Energimyndigheten, 2021)
Cost for truck driver inc. taxes	32000 SEK/month	(Lönestatestik, 2021-05-08, Skatteverket, 2021-05-08)
Working hours in a year	2080 hour/year	(Tillväxtverket, 2021-08-05)

With the following equations, data from Table 13 and Table 14 are converted into the values reported in Table 15.

Mean speed:

$$\frac{km}{year}\Bigg/\left(\frac{\frac{working\ hours}{year}}{\frac{normal\ working\ hours}{day}} * \frac{truck\ driver\ working\ hours}{day}\right)$$
$$= 70\ 000/\left(\frac{2\ 080}{8} * 12\right) = 22\ \frac{km}{hour}$$

Mean transportation time:

$$\frac{mean\ distance * 2}{mean\ speed} = \frac{15 * 2}{22} = 1.34\ \frac{hours}{load}$$

Depreciation of truck:

$$\frac{depreciation}{year}\Bigg/\frac{distance}{year} = 420\ 000/70\ 000 = 6.00\ \frac{SEK}{km}$$

Wear cost for the truck:

$$\frac{wear\ cost}{month} * \frac{month}{year}\Bigg/\frac{distance}{year} = 6\ 500 * 12/70\ 000 = 1.11\ \frac{SEK}{km}$$

Cost for truck driver:

$$\frac{salary\ incl.taxes}{month} * \frac{month}{year}\Bigg/\frac{working\ hours}{year}\Bigg/\frac{km}{hours} = 32\ 000 * 12/2\ 080/22 = = 8.23\ \frac{SEK}{km}$$

Diesel cost tank truck:

$$\frac{litre\ diesel}{km} * \frac{SEK}{litre\ diesel} = 0.65 * 16 = 10.40\frac{SEK}{km}$$

Diesel cost container truck:

$$\frac{energy}{km} * \frac{SEK}{litre\ diesel}\Bigg/\frac{energy}{litre\ diesel} = 3.5 * 16/9.8 = 5.71\frac{SEK}{km}$$

Total cost tank truck:

$$deprec. + wear\ cost + driver + diesel = 6.00 + 1.11 + 8.23 + 10.40 = 25.74\ \frac{SEK}{km}$$

Total cost container truck:

$$deprec. + wear\ cost + driver + diesel = 6.00 + 1.11 + 8.23 + 5.71 = 21.06\ \frac{SEK}{km}$$

Table 15 - Conversion of data from Table 14 (the same as Table 9)

	Calculations
Mean speed divided over a day	22 km/h
Mean transportation time	1.34 h/load
Depreciation of truck	6.00 SEK/km
Wear cost for the truck	1.11 SEK/km
Cost for truck driver	8.23 SEK/km
Diesel cost tank truck (slurry)	10.40 SEK/km
Diesel cost container truck (solid)	5.71 SEK/km
Total cost tank truck (slurry)	25.74 SEK/km
Total cost container truck (solid)	21.06 SEK/km