Norwegian University
of Life Sciences

Master's Thesis 2017 30 ECTS
School of Environmental Sciences and Natural Resource Management

Optimising the utilisation of agricultural manure for biogas production

A model based on the county of Vestfold in Norway

Mia Bjerkestrand
Renewable Energy

Acknowledgements

This thesis was written as the closure to my two-year masters-program in Renewable Energy at the Norwegian University of Life Sciences (NMBU), 2017. It is written by me, Mia Bjerkestrand, under careful supervision of Ole Jørgen Hanssen. The study and model is compiled for, and in collaboration with, Østfoldforsking AS. and will be used for further research in their BioValueChain project as well as Kari Anne Lyng's PhD. For more information about these projects, please see Østfoldforskning's website.

Writing this thesis has been a challenging, educational and exciting experience for me. The thesis is a product of the themes I have enjoyed the most during my time at NMBU: renewable energy and waste management. It has ignited a passion for circular economy and biogas issues, not only as a renewable energy, but a way to implement circular economy to create e valuable resource from waste. I have also gained a deep respect for the skilled people working with these issues. The result is a thesis and model that can hopefully give some insight into the complexity of farm produced biogas and the possible optimal solutions.

There are a lot of people who deserves acknowledgments and my gratitude. First and foremost, I want to give a huge thank you to my wonderful supervisor Ole Jørgen Hanssen, for the great support and guidance he has given me. Further appreciation must be given to two wonderful ladies from Østfoldforskning who have helped me with the linear programming, data-gathering, and validating of the data: Aina Stensgård and Kari Anne Lyng. They have provided me with support and constructive criticism whenever I needed it. I also want to thank all the people who have provided me with data directly from their research or databases: Rune Bakke, Jon Hovland and Mariann Hegg.

Lastly I want to thank my amazing family, friends, and my wonderful boyfriend for getting me through this trying time in my life. The time spent working on this thesis, as well as my time as a student here at NMBU, would have been miserable without all of you.

Mia Bjerkestrand

Abstract

The threat of climate-change and the harm it is doing to the Earth has been known for a long time, and the worlds countries have come together to try to limit the damages humanity is doing. The result is multiple international conventions and agreements, most recently the Paris-agreement in 2016. Norway ratified the agreement and implemented the goals in November 2016, and have since searched for solutions to reduce the overall emissions of harmful gasses to the atmosphere. One of these goals was to produce more renewable energy.

This thesis focus is the production of the renewable energy carrier biogas. Specifically, the production of biogas from farm manure. Agriculture in Norway is the fourth largest contributor to Norway's emissions of greenhouse gasses, and production of biogas from manure and other wastes has a significant potential to reduce these emissions. The thesis is developed around a case-study considering Vestfold county and the farms with livestock production within the county, and how they can participate in the production of biogas.

The thesis considers 50 farms and the main deciding factors when choosing to produce biogas or not: their potential costs/income and the potential reduces GHG-emissions. To find the optimal solutions between those two factors, an optimisation model was developed. The results from the model was an overall summarised economy and reduction of emissions for every farm, as well as for each farm. The model was solved for two scenarios where the farms either use electricity or burning of woodchips to provide the demand for heat at the farm. The model's initial results showed a great potential of reduction of 474-528 tons CO_2-equivalents should all farms choose to follow the model's recommendations. The initial solution also show that production of biogas can be a source of income. The initial solution resulted in a total income of about 150 000-419 000 NOK summarised for all farms. These results show that production of biogas is both profitable for farms, and a valuable measure to reduce GHG emissions.

A sensitivity analysis of the initial results derived from the model showed that an optimisation model can be a valuable decision-making tool when looking at a given number of farms in a given area, and give insight to the potential gains should the choices be implemented. However, there is still uncertainties surrounding the data in the model, and some of the calculations. These factors must be processed and quality assured before the model can be taken seriously.

Table of Content

Acknowledgements 2
Abstract 3
Figures 6
Tables 6
1 Introduction 7
2 Purpose of the thesis and research questions 9
3 Appraisal and focus 11
3 State of knowledge 13
3.1 Biogas potential in Norway 13
3.2 Biogas models 14
3.3 A Multi objective optimisation model considering biogas 15
5 Study objects and data gathering 17
5.1 Alternative decisions to be tested in the model 17
5.2 Technological data and restrictions 18
5.2.1 General information and Alternative 1 18
5.2.1 Alternative 2 19
5.2.3 Alternative 3 20
5.3 Agricultural data and restrictions 21
5.4 Economical data and restrictions 22
5.4.1 Alternative 1 22
5.4.2 Alternative 2 23
5.4.3 Alternative 3 23
6 Optimisation model – design and construction 25
6.1 Management Science 25
6.2 Optimisation 26
6.3 Excel Solver 27
7 The MOILP-model formulated in Excel Solver 29
7.1 Indices 29
7.2 Parameters 29
7.3 Variables 32
7.4 Formulas and calculations 32
7.5 Constraints 35
7.6 Objective functions 36
8 Results 38

8.1 Initial results ... 38
8.2 Sensitivity analysis ... 43
8.2.1 Sensitivity in demand for energy ... 43
8.2.2 Sensitivity for distance ... 45
9 Discussion ... 47
9.1 Uncertainties in the datasets and calculations ... 47
9.2 Choice of software ... 48
9.3 Realistic implementation ... 49
10 Conclusion ... 50
11 Further research ... 52
12 References ... 53
Attachment 1 ... 56
Attachment 2 ... 57
Attachment 3 ... 58

Figures

Figure 1 Relationship between produced manure and biogas potential 22
Figure 2 The management science process (Tyler, 2016, p. 23) 25
Figure 3 Total amount of GHG emissions for both scenarios 38
Figure 4 Total amount of costs for both scenarios 39
Figure 5 Total costs for each chosen alternative for both scenarios 40
Figure 6 Total GHG emissions for each alternative for both scenarios 41
Figure 7 Comparing potential GHG emissions 42
Figure 8 GHG emission from decreasing and increasing energy demand 44
Figure 9 Costs from decreasing and increasing energy demand 45

Tables

Table 1 Indices 29
Table 2 Parameters included for general information 30
Table 3 Parameters that differ for each farm in general information 30
Table 4 Parameters included in Alternative 1 30
Table 5 Parameters included in Alternative 2 31
Table 6 Parameters included in Alternative 3 31
Table 7 Variables included in the model 32
Table 8 Formulas for calculations in general information 32
Table 9 Formulas for calculations done for Alternative 1 33
Table 10 Formulas for calculations done for Alternative 2 33
Table 11 Formulas used for calculations for Alternative 3 34
Table 12 Formulas used for calculations in the Biogas model 35
Table 13 The initial solution to the biogas model 42

1 Introduction

The Paris-agreement in 2015 saw almost all world leaders coming together to accept one common goal: Keeping the worlds temperature-increase below two degrees Celsius compared to pre-industrial levels (Paris agreement, 2015). All parties that acknowledged the agreement must put forward their best effort to achieve the goal. To reach the goal, the UNFCCC has produced multiple articles that are legally binding for the countries as to how they may implement strategies in their governing framework. Norway ratified the agreement the 20th of June 2016, and committed themselves to reduce their greenhouse gas(GHG) emissions by 40% by 2030 (Regjeringen.no, 2016).
Concrete regulations and legislations for Norway's way forward are to be determined by 2018, and are presently being developed, but suggestions for mitigations have been researched and stated. Norway has several areas that emit large amounts of GHGs. The areas that emitted the highest amount in 2016 was oil- and gas-production, industry, transportation, and agriculture (SSB, 2016).
Norwegian agriculture might not be where the reduction of emission of GHGs is most pressing, but the Norwegian environment Agency (Miljødirektoratet) published a report that presents different class of measures to reduce GHG emission in the non-quota limited sectors, where Norwegian agriculture is described (Andersen et al., 2015). The measures presented for agriculture were changes in the Norwegian diet, stopping new cultivating of bogs, and production of biogas from manure. According to the SSB-source, agriculture emits 8,4% of Norway's total emissions. This amounts to 4,5 million tons of CO_2-equivalents (SSB, 2016). The potential for reduction in Norwegian agriculture has been measured to be 1,0 -1,5 million tons CO_2-equivalents by introducing new strategies and technologies, among these are biogas-production (Meld. St. 39, 2008-2009). For this reduction to happen, the Stortingsmelding decided to make production of biogas a national goal, and proclaimed that 30% of the produced manure should go to biogas-production.

Biogas-production in Norway have become of increasing interest due to improved or new technologies and governmental support. The realistic potential for biogas-production in Norway is estimated to be 950 GWh, without the inclusion of industrial waste (Lånke et. al., 2016). The same research concluded that 300GWh of this potential can be produced from agricultural manure. To reach this potential, it is vital to make production of biogas viable for the farmers around the country.

The farms are the source of manure, and have gotten a lot of governmental support for the possibility of biogas-production, e.g. financial support for delivering their manure to a biogas-plant. The farmers have two choices when the want to produce biogas. They can produce biogas from their livestock manures locally on the farm, or send the manure to a centralised biogas-plant. The local reactor is called Telemarksreaktor, and can produce heat from biogas and biofertilizer on the farm. One of the larges biogas-plants in Norway is located in the county of Vestfold, in the eastern part of Norway. The name of the plant is GreVe Biogass. This is the only current large biogas-plant that produces biogas based on manure from farms (Lånke et al., 2016). Vestfold was therefore chosen as the objective for this case study.

The county of Vestfold is home to some of Norway's biggest farms, and hence the county with the most available amount of manure. Vestfold has also included the production of biogas in their strategy for the future 2020 goals (Vestfold fylkeskommune, 2015). Because of these goals, the county's farmers, as well as the rest of the farmers in the country of Norway, must decide how they will reach the 30% goal set by the government. Vestfold's County Council has presented their goals for a growth in Vestfold's biogas production, and consequently that all farmers, big or small, in Vestfold must make a choice of whether they want to be a part of this development or not. This thesis will focus on 50 farmers, their livestock, and their alternatives for production of biogas.

2 Purpose of the thesis and research questions

The purpose of this thesis is to give the agriculture sector, as well as specific farmers, a good decision-making tool when facing a choice of whether or not to produce biogas from manure, as well as showing how it is possible to do it. The tool chosen to analyse the alternative solutions is an optimisation model. It will allow the farmers to see the big picture of how their locally produced manure can be a source of renewable energy, contributing to reduction of GHGs emissions, and as a potential source of extra income. This tool will not only show results for the farmers, but also other interested parties the theoretical optimum solution to which farms should contribute to biogas-production, how the biogas should be used, and how much it will cost in investments and operation. The outcome of the model will show the number of farmers and their geographic localisation that should produce their own biogas locally, the number and localisation of those that should send their manure to GreVe biogass, and the number of farms that will not be a part of biogas-production in Vestfold. The outcome is expected to answer the research questions shown later in this section, by providing a model-output that shows the optimal solution for each of 50 farms included in the analyses, as well as the optimal solution for the whole county.

This thesis will focus on how to optimise the local conversion from direct spreading of manure from cattle and pigs on crop-fields, to local or central production and use of biogas and biofertilizer, with a case-study consisting of farms located at different distances from GreVe Biogas in with Vestfold county as a case-study.

To get a holistic picture of how the production of biogas can be optimised in the county, an optimization model has been developed. The model is developed with Multiobjective Integer Linear Programming (MOILP), to give the farms a good decision-making tool that accounts for the environmental and the economic aspects of production of biogas. The thesis will focus on developing the pilot model in Excel Solver. The model will include limits for transportation to the big centralised biogas plant GreVe Biogass, the conditions that apply to and if the local farm-based biogas reactor is economically feasible, as well as the complete picture of GHG emissions in Vestfold should the resulting choices be applied. The research questions formulated to reach this thesis' purpose is presented below in the order in which they will be discussed:

i. Is it possible to develop an optimisation model in Excel that can analyse the use of manure from cattle and pig farms in a region with meaningful results?
ii. What is the limit for transport of manure to a central biogas plant compared to treating the manure at the farm?
iii. Under what conditions is it more feasible for the farmer to invest in his/her own biogas plant?
iv. What is the net GHG emission of biogas production at farms or treatment at central biogas plants, compared to a scenario where the farmer continues to use their manure without any changes?

3 Appraisal and focus

An optimisation-model is suggested to solve the before mentioned research questions. When such a model is suggested as a tool, it is important to recognise that the model must be framed within a set of appraisals and within a certain focus. A model, however thorough the programmer might be, is limited to give the reader insight into the problem only. The construction of a model is a method to simplify reality's complex problems. The model constructed should therefore never be considered the absolute truth, as it can never be as complex as reality (Taylor, 2016). This chapter will present the different appraisals and the limitations of solving the research questions this way, and should be considered when analysing the end results and conclusions.

To get a good representation of the potential reductions in costs and GHG emissions, an analysis of two scenarios will be conducted. These two scenarios depend on the farms energy carrier for their demand for heat at the farm. The model will be solved for one scenario where all farms utilize electricity from the standard Nordic mix to meet the demand for heat, and another scenario where all farms utilize an oven that burns woodchips to meet the demand for heat.

When deciding to produce biogas, there is a lot of different factors to consider. For instance costs, possible income, the environmental effects, extra work for the farmer, and the farmer's general willingness to participate in such a venture. This thesis has only considered the first three factors. This is because the focus of the thesis is to analyse the most important factors in a system like this. Most important for society, the country, and the climate are the environmental factors, and the most important factors for the farmer is his/her own economy. If the farmer can gain enough to make the investment, and time put into the project, profitable, the more likely he/she is to go through with it. The environmental factors are comprised into CO_2-equivalents to gather all the different factors, such as NO_x, CH_4, and CO_2, into one, stand-alone factor.

The biogas produced at the farm, should the farmer choose to invest in a local reactor, will be utilized to replace the demand for heat for the farm's livestock. There are certainly other options as to what the energy from the reactor might be used for, for instant heating the main farmhouse or other buildings in the vicinity, but the focus for this thesis is to get enough energy from the reactor to replace the demand for heat at the barn should the small reactor be the optimal solution. Furthermore, it is assumed that the farms have one of two different energy carriers that provides heat at the farm. These are either woodchips or electricity. It is therefore conducted two scenarios when solving the model. One where all farms use electricity, and one where they all use woodchips. The electricity source is the standard Nordic mix. The biogas produced will replace the potential GHG emissions from the storage of manure and the potential GHG emissions from the replaced energy carrier. All data from the farms are from 2015, and the other data in the model will therefore consider data from 2015 to give insight into this particular year.

The biogas produced at the centralized biogas plant (GreVe biogass) will be upgraded to biomethane and utilized as fuel to replace diesel. The GHG emissions for the farm's use of energy carrier will be considered, as the biogas produced replaces nothing at the farm. The only GHG emissions saved at the farm will be a potential reduction because the farm must invest in a new tank for storage of the biofertilizer they get in return.

The costs considered for the model is the farm's investment cost for all the possible alternatives calculated for yearly cost, and the cost for the demanded energy carrier that supplies heat for production of livestock. The income considered is the potential for governmental support from their participation in production of biogas, as well as their potential investment support from Innovasjon Norge. These numbers are all calculated for each alternative and compared.

The model aims to find a solution on how to reach two main goals: to minimise the overall GHG emissions in Vestfold, and to minimise the overall cost for the farm. To do this, weighing has been set to the goals, and an end goal has been considered. The weights are one for GHG emissions and one divided by the given price for CO_2-quotas in 2015. The model will find two different optimal solutions to the cost- and emission goals, compare the deviation between them, and calculate a new solution where the optimal result is where the deviation between the stand-alone goals are minimised.

3 State of knowledge

3.1 Biogas potential in Norway

As Norway aims to move towards a future with less GHG emissions, it has been important to assess all possible alternatives to reach the 2020 goal given by the EU. Biogas production has been proven to reduce GHG emissions from agriculture, by reducing the methane emission from stored manure and supply climate-neutral methane that will be used for energy purposes (Morken et. al., 2015). The Ministry of Climate and Energy has developed a strategy on developing biogas in Norway to contribute to reducing Norway's GHG emissions. According to this document the production of biogas in Norway in 2010 from organic waste and manure from farms was only 0,06TWh (Sundtoft, 2014). The department stated further in the strategy that almost all biogas produced is used as fuel for buses or other vehicles used for heavy transport. The demand for biogas could be much higher. Buses and lorries around the country are now transitioning into using more and more natural gas, and they could use biogas, if there was available supply. The estimated possible production is calculated to be 2,3 TWh every year (Sundtoft, 2014).

A study conducted by Avfall Norge published in 2016 looked at the possibility of both growth in production in biogas produced as well as economic growth in the eastern region of Norway (Fiksen et. al., 2016). This region includes Østfold, Vestfold, Oslo, Akershus, Telemark, Buskerud, Oppland, and Hedmark. The growth will be highest in this region because of its agricultural productivity. The purpose of the study was to see the potential for growth of biogas and to visualise the economic growth that is possible to gain through more development of biogas plants and bio waste (Fiksen et al., 2016).
The study was conducted for Avfall Norge and Biogass Oslofjord. They have identified the value chains that are, or will be, developed to showcase potential production of biogas in the Oslofjord area. They used an analysis of ripple effects to measure what kind of effects the development will have, not only in the economic field, but what effects the development of industry will have on economics and employment. This was done to give a better perspective of what development of more biogas could do for society in the given region of Norway. The study then went on to describe what the biogas field looks like today, to get a better view of what can be possible in 2020. Biogas and bio-waste in the eastern part of Norway can produce 440 GWh. With the available resources, and the new strategies in place to reduce GHG emissions, and a possible transition into a circular economy, the study concluded that the

realistic potential in the studied region was 2000 GWh. To reach this amount of produced energy, the amount of food waste, manure, and waste from industry delivered to biogas plants must increase. The study didn't specify any weaknesses with their results, but it is stated that this is a prediction. The future might be different, but the study gave a solid view of the future of biogas in the given region.

3.2 Biogas models

Another model that considers biogas production in Norway is the BioValue Chain model. This model was constructed to facilitate the calculation of environmental impacts throughout the value chain for production of biogas (Lyng et al., 2015). The purpose of this model is to provide a model that easily can generate an impact assessment. The model is based on life cycle assessment methodology with system boundaries and parameters that can be changed easily to accommodate for every biogas plant or region. The model needs specific data, and when this isn't found, the results can be uncertain. The authors suggest that more research will have to be done within the field of "modelling and quantifying direct emissions from the storage and application of manure and digitate on land" (Lyng et al., 2015).

Another study from the Netherlands, studied the increasing initiatives for biogas production and what may come from this. The article looks at producing biogas, but also the possibility of using the resources to produce combined heat and power (Hengeveld et. al., 2016). They developed a model that calculated the costs and environmental benefits of creating a fish-bone system to collect biogas from farms and transport them through a pipeline to a centralised plant. The model showed how cooperation of biogas producers reduces the transport costs for the total area. The author states that there should be further research conducted for the possibility of transporting liquid biogas through the same pipelines, and the flexibility of the energy supply should be researched further.

As an alternative to sending the resources to far away centralised biogas plants, the resources could be used more locally. They could be used to produce biogas, heat, and power locally for the farmers. Studies that will be presented in this section will show different ways of using these resources differently.

The resources that exists outside the economical optimal distance from the big centralised biogas plants can be optimally used close to where they are generated. A study conducted by DisBiogass showed research that looked on four different scenarios. The scenarios looked at different uses of the farm possible biogas- resources (Modahl et. al., 2014). Scenario 1 focused on central biogas production and central upgrading. Scenario 2 focused on local biogas and local utilisation. Scenario 3 focused on local biogas production but central upgrading. Scenario 4 focused on the same, but the biogas was transported to the central upgrading plant through pipelines. There was also a reference scenario, where the manure was left untouched. The purpose of the study was to "contribute to the development of more cost effective and sustainable biogas production and distribution technologies from small and distributed farms in Norway" (Modahl et al., 2014). To best present the scenarios the Biogas Model from Østfoldforskning was used. The conclusions that was the result of this research was that all the scenarios that produced biogas was preferable to the reference scenario. They also concluded that the use of biogas as fuel for transport is better than using it for heat. Furthermore, the study concluded that a local biogas plant and a central upgrading plant was preferable to transporting the manure to a centralised biogas plant. How the biogas gets transported to the centralised upgrading plant is negligible. They have used some general assumptions in the research, and these might be worth checking further. The numbers used for the economy section of the article might be too general and will change when area and technological development is considered.

3.3 A Multi objective optimisation model considering biogas

When we want to find the optimal solution to a complicated problem with two conflicting objectives a multi-objective optimization model is well suited. In the study conducted by Silva et. al (2017) regarding multi objective programing for sizing and locating biogas plants, she showcased the use of this method by solving a problem with multiple conflicting objectives: minimizing initial investment cost, operation, and maintenance cost; minimizing transport costs; and minimizing social rejection. The purpose of this study was to find a Pareto-optimal solution, where the result is a solution where all objectives are impossible to improve without worsening the other objectives. The economic and social objectives in this study conflicts with each other by their potential economic value and the social term "not in my back yard" (NIMBY), where the residents of a given area may see the value in the investment, but greatly oppose the investment being done close to their homes. Silva et. al. (2017) then proposed a Multi Objective Mixed-Integer Linear Programming (MMILP), which operates with binary variables, to highlight the decision being made by this model. They have the choice of multiple possible locations for the biogas-plants, and the models purpose is to help the Entre-Douro-e-Minho Region in Portugal to select the most optimal location(s) by finding Pareto-optimal solution for the three objectives.

The parameters included in the model was assumed and gathered for each dairy farm in the area, each possible location for biogas-plant, type of biogas-plant, and social data for each parish. The variables were both binary and real. The variables represent choice of dairy farm, amount of manure transported, and type of biogas-plant. To get the most optimal choice from these variables, the objectives was scaled and combined into one objective by applying each objective a weighting-factor. This ensures that all solutions are underlined preference weights. The result was a selection of biogas-plants, where they should be placed, and their cost. To check the result, a sensitivity-analysis was conducted, and they showcased numeral different results when parameters were changed. They concluded with stating that this is a model with limitations and should only be used as an insight into what is possible in the region, and that their limitations can be reduced by larger terms of variables and larger amounts of data.

As a Multi Objective Integer Linear Programming (MOILP) model, considering biogas production in Norway, has not been developed before, the thesis aims to build on the existing knowledge presented here. The MOILP will hopefully give insight to new solutions for the way biogas from livestock manure can be produced the optimal way for both the environment and the farms economy.

5 Study objects and data gathering

The data for the thesis was mostly collected through interviews, and personal conversations with people closely connected to the biogas community in Norway, as well as other research journals and articles. The interviews and meetings were conducted through mail or the conversational software: Skype to easily communicate with the participants. All study objects have their own restrictions and possibilities, and will be presented in their own subchapter, with restrictions stated and explained. The data needed to answer the previously stated research question was a challenge to find, as the data had to be very specific and detailed to get a credible solution to the model. An overview of the localisations of the 50 farms included in the model are presented in Attachment 1.

5.1 Alternative decisions to be tested in the model

The model will have three alternative decisions that the farmer must choose what to do with manure produced at the farm. The model will suggest the alternative that is most favourable for the farmer, considering the farmer's economy and the environmental impacts. In Alternative 1, the manure will be used directly as a fertilizer as it is today, without involving production of biogas or investment in a new tank. In Alternative 2 the farmers will invest in a small-scale biogas reactor adjacent to the farm and use both the biogas and the bio-fertilizer locally. In the third alternative is Alternative 3 farmers will transport the manure to GreVe biogas plant for producing biogas and upgrading to fuel.

Other alternatives like collective production of biogas between three to five farms were considered, but found to not be viable because of the strict rules for mixing of manure from different farms. This rendered the alternative with all the output of biogas having to go to the washing of the manure.

Alternative 1 is the reference scenario as well as an alternative for the optimal solution. The farmer will not produce biogas, neither locally on his farm or send his or her manure to GreVe biogass. This means that the farmer has emissions from the storage of manure and the energy-carrier used for heating. The respective data for emissions are derived from research done by Østfoldforskning and their BioValueChain project. The farmer will not have any investment-cost, and will also not have any new income. The numbers related to emissions differ from what type of livestock the farm produces. For each ton of manure from pigs produced at the farm 21,1 kg CO_2 equivalents are produced, and for each ton of manure from cattle that is produced 38,2 kg CO_2 equivalents are produced (Lyng et al., 2015).

Alternative 2 is the alternative that chooses the Telemarksreaktor as the optimal solution to the specific farm. Should this alternative be chosen, the farm will invest and build their own biogas-reactor locally at the farm. As much manure as needed to keep the Telemarksreaktor running and producing biogas will be used by the farm, and the resulting biogas will be used to provide heat for the livestock at the farm. The biofertilizer produced by the reactor will be used on the field as if it was regular manure, with no assumptions of biofertilizer being a better alternative to regular manure.

Alternative 3 is the alternative that chooses that all the manure from the farm should go to the centralised biogas-plant GreVe biogass. Should this alternative be chosen, all the manure will go to the production of biomethane to be used as fuel in transportation, and the biofertilizer will be returned to the farm. The farm will therefore have to invest in a new tank to hold the biofertilizer at the farm, as well as give 2/3 of their governmental support to GreVe biogass (Hegg, 2017). There is no assumption that the delivered biofertilizer from GreVe biogass is better than regular manure.

5.2 Technological data and restrictions

Each alternative studied in this thesis will differ largely from one another technologically and economically, as well as regarding GHG-emissions. The technological restriction for each alternative is determined by type of plant, transport to and from the reactor, and size of the plants. Each reactor and plant for both alternatives that includes production of biogas have different data and restrictions, and are presented below.

5.2.1 General information and Alternative 1

As there is no change in technology in Alternative 1, the data and restrictions for this alternative will not get its own subchapter, but be complied together with the data and restrictions for general information. The only thing that needs to be mentioned about this alternative is its GHG-emissions. Kari-Anne Lyng calculated these numbers to be 38,2 kg CO_2-equivalents per ton cattle manure and 21,9 kg CO_2-equivalents per ton pig manure. The GHG emissions from burning woodchips to meet the demand for heat, is valuated at 0 because of the source being part of the natural carbon-cycle. The GHG emission from the Nordic energy mix used to meet the demand for heat is assumed to be 0,128 kg CO_2-equivalents per kWh (Larsen, 2016).

The demand for energy on the farm was difficult to obtain. The data for energy demand per pi for heating of burrows was collected from a paper published in England. The number was chosen because the climate in England is similar to the climate in the eastern part of Norway, and the demand for energy is therefore assumed to be the same. The demand used in this thesis is 8,4kWh/pig/year (TheCarbonTrust, 2016). The demand for energy for cattle was calculated from one farm in Østfold county provided by Ole Jørgen Hanssen through personal communication by e-mail, and the number proved to be viable when comparing the number to other farm's cost of energy calculated by TINE and André Brockstedt Myrseth through personal communication. The energy demand for cattle used in this thesis is 1789,5 kWh/cattle/year. The demand on each farm is calculated for each individual farm by multiplying these numbers with the number of livestock at the farm.

5.2.1 Alternative 2

All the information on this reactor was obtained from its creators: Rune Bakke and Jon Hovland through e-mails and meetings. This resulted in the most accurate data as possible for this reactor. This is a new technology, but it is well on the way to become a viable commercialised option for locally produced biogas. This small-scale biogas reactor can treat manure from a minimum of $5m^3$ manure to a maximum of $10m^3$ per day. The manure is fed into the reactor by pulse-feeding. This means that the manure is continuously fed little by little over the course of the day. The reactor needs to be fed at least 1m3 manure every day to maintain the culture inside the digester. This was the leading factor in deciding which farms that were applicable for the model. The manure ton to m^3 ratio is assumed to be 1:1 because of the manure contains 92% liquids (Lyng et. al., 2015). The maximum capacity for the Telemarksreaktor is therefore assumed to be 2840 tons per year. The reactor has the capability to produce $10\text{-}50m^3$ of biogas per day, depending on the amount input of manure.

Efficiencies must be included here as a restriction to the reactor. The overall efficiency of the Telemarksreaktor is set to 60% of the biogas-potential from manure (Lyng et al., 2015). This means that the reactor can only produce 60% of the amount calculated from manure using standardised numbers. Furthermore, there is a restriction on the amount of heat the reactor can produce from the amount of biogas produced from the manure. After this calculation is done, the biogas needs to be converted from Nm^3 to kWh. This is done by using a standardised number calculated by Kari-Anne Lyng: 6,07kWh per Nm^3. The efficiency from heat production is set to be 85% (Lyng et al., 2015). This means that 85% of the potential energy from the biogas produced is transformed into heat for the farm to utilise. These numbers are used to calculate the potential heat production from the reactor in kWh. This differs for all farms, except from the farms that have enough manure to reach the full capacity.

The production of biogas does emit GHG's from for instant storage of manure and GHG emissions from the use of the biogas. These emissions numbers are calculated by Kari-Anne Lyng. She calculated numbers for cattle and pig manure respectfully in the different scenarios when the demand for heat is met by either electricity or woodchips, and the numbers used in this thesis is 10,8kg CO_2-equivalents per ton cattle manure and 9,4kg CO_2-equivalents per ton pig manure for the scenario with woodchips, and 9,4kg CO_2-equivalents per ton cattle manure and 5,8kg CO_2-equivalents per ton pig manure. These numbers were provided by Kari-Anne Lyng.

5.2.3 Alternative 3

The GreVe biogas-plant is the only big, centralised biogas plant that produces biogas from farm manure in Norway (Fiksen et. al., 2016). The biogas-plant is located just outside Tønsberg in the county of Vestfold, and produces biomethane from manure from 45 farms in the same county. It was officially opened in September 2016, but had produced biomethane a while before (Woll, 2016). If the manure would be transported to GreVe biogas, it would be upgraded to gas-fuel and replace diesel as an energy source in busses and other heavy transport vehicles.

When anything is converted to something else it is subject to the efficiency of the technology utilized in the converting. When GreVe biogass collects manure from the farms and converts this into biomethane through anaerobic digestion in the biogas plant, it will be subject to the amount of biomethane the plant can produce divided from the biogas potential from the manure of the conversion had an efficiency of 100%. The overall efficiency of GreVe biogass is 70% (Lyng et al., 2015).

The biomethane that GreVe biogass produces replaces diesel as fuel for heavy transport, like lorries and busses. Kari-Anne Lyng and the researches at Østfoldforskning have done extensive research on the potential reduction of GHG emissions when using biogas instead of diesel. After some updating done by Lyng herself, she concluded that with possible reduction values for each type of manure utilised in the production of biogas, cattle or pigs, the numbers are respectfully -5,3kg CO_2-equivalents per ton and -14,5kg CO_2-equivalents per ton (Lyng, 2017). These are the GHG emission number that will be used to calculate the emission potential for Alternative 3.

GreVe biogass has no restrictions as to how much manure they can store and produce biogas from, and no specified distance they will not travel to, to obtain the manure, if it is within reason for the potential GHG-emissions from transport (Hegg, 2017).

If the optimal decision for the farmer is to send the manure to a centralised biogas plant, the parameters for fuel consumption and GHG-emissions from lorries must be recognised. This is calculated in the model from a generalised algorithm developed by Kari-Anne Lyng in her BioValueChain project. She calculated this number to be 0,087 kg CO_2-equivalents for each ton-kilometre driven by the lorry. This means that every ton of manure transported one kilometre by lorry produces 0,087 kg CO_2 equivalents. This was taken into account by multiplying the amount of manure produced at the farm with the farm's distance to GreVe biogass. This yielded all the possible GHG emissions from transport of all the farm's produced manure.

5.3 Agricultural data and restrictions

All farms used as study objects in this thesis have their own set of data and restrictions. They all differ in localization and distance to the GreVe biogas plant as well as to production of manure, and therefore biogas-potential. The type of energy carriers that are used, and which can be substituted for by changing to biogas, varies. Some of the farms included in this study are big farms with more than 2000 animals, others might just have enough livestock to comply with the technological restrictions for the Telemarksreaktor.

All farms in Vestfold county were considered for the analyses, but only farms that produce at least $5m^3$ manure per day from cattle and/or pigs were selected. Cattle production include suckling cows, dairy cows and other cattle (heifers and calves). Pig production includes breeding pigs and pigs for slaughter. These types of livestock and their manure have been chosen for this thesis because of the previous extensive research that has been done into how much biogas they have potential to yield (Karlengen et. al., 2012; Lyng et al., 2015; Raadal et. al., 2008). The biogas potential from sheep, horses, and poultry are more uncertain and has not been included.

Furthermore, it is assumed that the manure from cattle and pigs include 92% liquids and 8% dry matter (Lyng et al., 2015). These numbers are used further by calculating the potential biogas yield from the given amount of manure the farm produces.

The number of different types of cattle and pigs are vital to calculate the biogas potential. All the numbers for number of livestock was provided by Fylkesmannen in Vestfold: Jon Randby.

He provided a thorough set of data considering all the individual farms in Vestfold as well as all their livestock throughout a span of one year. Because of the restrictions on the small-scale reactor, all farms that cannot meet the demand for at least 5m3 manure per day have been omitted. Consequently, only 50 of the farms in Vestfold are considered implemented in the model. The remaining farms have been complied into figure 1 to get a better view of the relationship between produced manure and produced biogas.

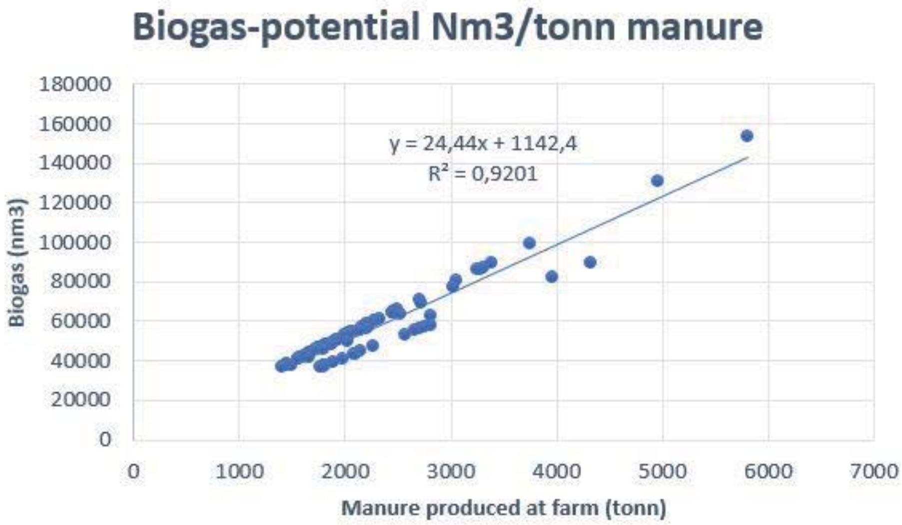


Figure 1 Relationship between produced manure and biogas potential

5.4 Economical data and restrictions

All the different farms will have different economical situations depending on where they are located, their income, expenses, and hence, their potential to invest in production of biogas. The economic data was found by calculating the amount of support they can get from the Norwegian government by producing biogas, the investment cost for each of the alternatives that will produce biogas, finding their yearly cost/income-potential, and the net present value (NPV) of the invested project.

5.4.1 Alternative 1

The economic data and restrictions for Alternative 1 are not very extensive, because of the farm's choice to continue as they do. The economic data included in the model for Alternative 1 is the cost they have for the demand they have for heating at the farm. This is calculated for both scenarios: utilisation of electricity and woodchips. The cost for electricity was found to be 0,548 NOK per kWh demanded (Hanssen, 2017), and 0,31 NOK per kWh demanded for woodchips (Grønn varme i landbruket, 2014). The total cost for energy at the farm is calculated with these numbers multiplied with the energy demand for each unit livestock at each individual farm.

5.4.2 Alternative 2

The costs for Alternative 2 is more complicated than those for Alternative 1. The Telemarksreaktor has an investment cost and an operation and maintenance cost. These numbers were provided from Rune Bakke (2017), and were calculated by him to be respectfully 1 million NOK and 30 000 NOK/year. Some of the farms could not produce enough heat from the reactor to meet their demand, so the cost for the extra needed energy had to be calculated. These were calculated from the energy needed and price for both scenarios.

When the farmers produce biogas, they receive support from both Innovasjon Norge and the government. The model is calculated with a 30% investment support from Innovasjon Norge. This number was provided from Aina Stensgård and her calculations on the cost of the reactor. The governmental support for producing manure locally at the farm is provided from the stated regulation of support for delivering manure to biogas production (2015). They have different factors for each different kind of cattle and pigs. The factors for cattle are 1660 NOK for each dairy cow on the farm, 950 NOK for each suckling cow, and 570 NOK for each other cattle on the farm. The factors for pigs are 340 NOK for each breeding pig and 34 NOK for each pig bred for slaughter.

All these costs and support gave the ground data for the calculation of the net present value of the investment, and further each yearly cost during the reactors lifespan.

5.4.3 Alternative 3

The costs and supports data for Alternative 3 are either provided directly from GreVe biogass (Hegg, 2017) or the regulation mentioned above. They have calculated that the cost for the investment of a new tank to store the biofertilizer the farm gets in return is compensated from GreVe Biogass by providing the farm with a price for renting. This price is provided from GreVe biogass to the farm based on the tank's size in m^3.

The governmental support for production of biogas from manure delivered to a centralised biogas plant is described in the regulation as $500NOK*x^2$, where x it the percentage of drymass in the manure (Forskrift om tilskudd for levering av husdyrgjødsel til biogassanlegg, 2015). This is different for each farm as each farm has different number of livestock, manure production, and therefore amount of drymatter. According to Hegg (2017) GreVe stated in their contract they sign with the farm that GreVe will receive 2/3 of the governmental support given to each farm from the government for delivering manure to biogas production.

6 Optimisation model – design and construction

The method chosen to find the best solution to this thesis' problem and research-questions was the excel software Solver. This software is used to find an optimal solution by linear programing. To use this software properly, and to make it work for this thesis, the focus was on management science and optimisation. The model was programmed with two objective functions and a comparative function that opted to find the point in the model where we can maximise the minimum deviation between the two objective functions.

6.1 Management Science

The method chosen to prepare the decision-making model is management science. Management science is defined as "[…] the application of a scientific approach to solving management problems to help managers make better decisions." (Taylor, 2016, p. 22). Considering the definition, management science is a good method to help the farmer to choose whether to produce biogas or leave their manure as is. Taylor explains further that management science follows a series of steps, closely resembling a scientific method, with a generally recognised and ordered set of steps shown in figure 2.

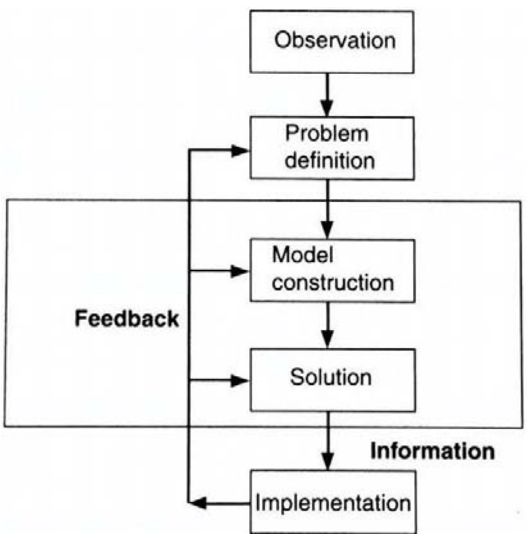


Figure 2 The management science process (Tyler, 2016, p. 23)

Figure 2 shows the way this model will be constructed. The need for a tool to help the in the farms decision-making regarding their participation in production of biogas is observed. The problem is defined in this thesis research questions. The model construction will consist of mathematical relationships between all the data that has been collected, their constraints, and the relationship between them and the objective function. A model is per definition an abstract mathematical representation of a problem that includes variables, parameters, and equations (Taylor, 2016). The model constructed for this thesis was based on this principle, and formulated mathematically through a method called optimisation.

6.2 Optimisation

Optimisation is one of the most popular methods to perform analysis in management science. It is a mathematical way of optimising a system that contains solid parameters, changeable variables, objective functions and constraints (Taylor, 2016). The purpose of optimisation and the optimisation analysis is to find a solution in the given system where all variables achieve Pareto-optimality. This is a state in which the results of allocation of the variables is optimised in a way that it cannot get better for one variable without it getting worse for another. This method creates a simplified model that gives insight into a complex problem, to help with decision-making. Because a model can only show a simplistic selection of reality, the result should never be considered the absolute truth (Taylor, 2016).

When an optimisation model is chosen to analyse a system, it either wants to maximise or minimise a functional relationship between all variables and parameters. This is called the objective function. The objective function is a product of all variables in the model multiplied with the parameters connected to them. The objective function is also underlined the model's constraints. The constraints in the model contains the possible solutions in the model by restricting the value of the variables. A typical mathematical formulation of an optimisation problem may look like this:

Maximise Z: \$Ax-Bx

Subject to: $Cx = 100$

$x \geq 0$

Where "Z: \$Ax-Bx" is the objective function where Z is a function of the number of units of the variable "x". Constraints are usually referred to as what the model is subject to. For instant could this example be applied to a company that wants to maximise their profit.

Theconstraintlimits the possibility to achieve infinite profit by limiting the decision variable "x".

The constraint "$x \geq 0$" represents that x must be positive, by limiting "x" to be greater or equal to 0.

Because the thesis presents three different alternatives to what they can do with the manure they produce, a Multi Objective Integer Linear Programming(MOILP) method has been chosen. When a model is integer, it ensures a solution with whole numbers rounded up or down to the nearest whole number. An integer model is a method for programming optimisation models where the variables that can either be programmed to be total integer, where all variables have an integer solution, a 0-1 integer programming, where the variables have integer values of zero or one, or mixed integer model, where not all variables are integer (Taylor, 2016). Since the model must choose between three alternatives, and only one of them can be chosen, the model will be programmed with 0-1 integer programing where the variables are either 0 or 1 depending on the choice.

Multi objective linear programing is a programing method that concerns two different objective functions. The two different objective functions analysed in this thesis are minimising of total emissions and the minimising of cost. MOLP is a category of models under the multi objective analysis umbrella. The constraints and objective functions are all linear. This is done to make a simple model that can be used and understood easily, and to simplify a rather complex problem. The two objective functions can conflict with one another, and a MOILP-model will break down the complexity. Once the model will be constructed and solved using the add-in software Solver in Microsoft Excel.

6.3 Excel Solver

There is multiple software that can perform a linear multi-objective optimisation, e.g. GAMS and CPLEX, but the software chosen for this thesis is a built-in software in Microsoft Excel called Solver. It has become the most widespread optimisation tool since its creation in 1991(Fylstra, Lasdon, Watson, & Waren, 1998). There are three reasons to why this Excel Solver was chosen for this thesis. The first reason is that Solver comes in every standardised package for Windows Excel, and is therefore readily available for everyone with access to Microsoft Office and Excel. This might make the model easer to replicate for further research and application of the model. Secondly Solver in Excel provides an easy way of entering and editing data. Because of this, it’s easy to change and rearrange the input into the model, and the model can be edited as new data arise (MacDonald, 1995). Thirdly Solver was chosen because of the limited amount of time this thesis was written in. The author had previous experience with this software, and could therefore shorten the time it would take to familiarise with it.

Excel Solver is an add-in into the Excel spreadsheets that allows for computer generated linear mathematical programming, and thus the integer linear programming that is used for this thesis (Taylor, 2016). Excel Solver's user interface combines the graphical user interface, an algebraic modelling, and optimisers for linear, nonlinear, and integer programs (Fylstra et al., 1998). When programing an optimisation model in Excel Solver, it starts in the regular spreadsheet in Excel. The objective functions and constraints are added through Solver after the model had been developed in the spreadsheet. Solver then creates a matrix from the information and produces one optimal solution for the programmed model.

7 The MOILP-model formulated in Excel Solver

Having now described all the data, assumptions and modelling options, this chapter will present the developed MOILP model in detail. As the definition of a model is a functional relationship between variables, parameters and equations, this chapter will go through all the variables, parameters and equations used in the model. This is a complex mathematical model, all parameters, variables, objective functions and constrains are given their own name and indices to help the reader keep track of everything. The indices are named to show what alternative the parameter is connected to. The parameters are named to shorten their long name, and to describe what they are. The variables are named to show their connectivity to parameters and the alternatives. And lastly, the objective functions, formulas, and calculations are all a compiled of the already named objects.

7.1 Indices

The model in itself is built around the premise of three possible alternatives to be evaluated and chosen. These alternatives all have different data, limitations, and layouts to them. All assumptions, calculations and constraints related to the different parameters must therefore be named by indices to make it easier for the reader to connect the parameter with its associated alternative or if it is a parameter connected to the general information.

Table 1 Indices

Abbreviation	**Explanation**
i	Parameter belonging to Alternative 1
j	Parameter belonging to Alternative 2
k	Parameter belonging to Alternative 3
l	Parameter belonging to general information

7.2 Parameters

The parameters included in the model as a basis for all other calculations are stated in the tables listed below. They are all the known data for the farm's general information, Alternative 1, Alternative 2, and Alternative 3. All parameters are given abbreviations to best represent what the parameter is representing. The tables also include short explanations for each parameter. For a more thorough explanation of the parameters, see chapter 5.

Table 2 Parameters included for general information

Abbreviation	**Explanation**
Dp_l	The percentage of drymass in liquid manure (8%)
$BiopC_l$	Biogas potential for drymass in cattle manure (Nm^3/tonTS)
$BiopP_l$	Biogas potential for drymass in pig manure (Nm^3/tonTS)
Epo_l	The potential energy from biogas (kWh/Nm^3)
EnP_l	The demand for energy per pig per year (kWh/pig/year)
EnC_l	The demand for energy per unit cattle per year (kWh/unit/year)
CCq_l	The cost of a CO_2-quota (NOK) in 2015
Elp_l	The price for electricity (NOK/kWh) in 2015
Wcp_l	The price for woodchips (NOK/kWh) in 2015

Table 3 Parameters that differ for each farm in general information

Abbreviation	**Explanation**
nDc_l	Number of dairy cows at the farm over the span of one year
nSc_l	Number of suckling cows at the farm over the span of one year
nOc_l	Number of other cattle at the farm over the span of one year
nBp_l	Number of breeding pigs over the span of one year
nSp_l	Number of pigs for slaughter over the span of one year
CM_l	Amount of manure collected from the farms cattle (ton)
PM_l	Amount of manure collected from the farms pigs (ton)

Table 4 Parameters included in Alternative 1

Abbreviation	**Explanation**
EmC_i	Emission from storage and spreading of cattle-manure (kg CO_2-equivalents/ton manure
EmP_i	Emission from storage and spreading of pig-manure (kg CO_2-equivalents/ton manure
$EmEl_i$	Emission from utilization of electricity to cover the demand for heat (kg CO_2-equivalents/kWh)

Table 5 Parameters included in Alternative 2

Abbreviation	Explanation
InC_j	Investment cost for the Telemarksreaktor (NOK)
OMC_j	Operation and maintenance costs for the Telemarksreaktor (NOK/year)
CaM_j	The Telemarksreaktor's maximum amount of manure (Ton manure/year)
OET_j	The overall efficiency of the Telemarksreaktor (%)
EHP_j	The efficiency of production of heat from the Telemarksreaktor (%)
InS_j	The total percentage of investment support from Innovasjon Norge (%)
LE_j	The Telemarksreaktors life expectancy (years)
$IntR_j$	The interest rate for the Telemarksreaktor (%)
$GsDc_j$	Governmental support for dairy cattle (NOK/dairy cattle)
$GsSc_j$	Governmental support for suckling cattle (NOK/suckling cattle)
$GsOc_j$	Governmental support for other cattle (NOK/other cattle)
$GsBp_j$	Governmental support for breeding pigs (NOK/breeding pig)
$GsSp_j$	Governmental support slaughter pigs (NOK/slaughter pig)
$ECrW_j$	Emissions when biogas from cattle replaces woodchips (kg CO_2-equivalents/ton manure)
$EPrW_j$	Emissions when biogas from pigs replaces woodchips (kg CO_2-equivalents/ton manure)
$ECrEl_j$	Emissions when biogas from cattle replaces electricity (kg CO_2-equivalents/ton manure)
$ECrEl_j$	Emissions when biogas from pigs replaces electricity (kg CO_2-equivalents/ton manure)

Table 6 Parameters included in Alternative 3

Abbreviation	Explanation
$ErFC_k$	Emissions from biogas replacing diesel as fuel (kg CO_2-equivalents/ton cattle manure)
$ErFP_k$	Emissions from biogas replacing diesel as fuel (kg CO_2-equivalents/ton pig manure)

EfT_k	Emission from transport of manure and biofertilizer (kg CO_2-equivalents/tonkm)
GsM_k	Governmental support for manure delivered to biogas production (NOK/TS)
OEG_k	Overall efficiency of GreVe Biogass (%)
DFG_k	Distance from the farm to GreVe Biogass (km)

7.3 Variables

The variables in the model are all binary as to assure that there can only be one choice made. The definition of a variable in management science is that it is a symbol that can take on any value (Taylor, 2016). They can only take on the number 0 or 1 in the model, and this represents the optimal choice made by the farm, whether it might be Alternative 1, Alternative 2, or Alternative 3.

Table 7 Variables included in the model

Abbreviation	Explanation
$X_{1\text{-}50i}$	Binary variable $X_{\mathbf{1\text{-}50}}$=1 if Alternative 1 is chosen, $X_{\mathbf{1\text{-}50}}$=0 if it is not
$Y_{1\text{-}50j}$	Binary variable $Y_{\mathbf{1\text{-}50}}$=1 if Alternative 2 is chosen, $Y_{\mathbf{1\text{-}50}}$=0 if it is not
$Z_{1\text{-}50k}$	Binary variable $Z_{\mathbf{1\text{-}50}}$=1 if Alternative 2 is chosen, $Z_{\mathbf{1\text{-}50i}}$=0 if it is not

7.4 Formulas and calculations

To calculate the multiple potentials for biogas production, emissions, and income/cost, a set of standard formulas was used for all 50 farms. These formulas have been formulated mathematically and programmed into Microsoft Excel. Most of these calculations could be set as constraints for the model, but to calculate them before they were put into the model served to make the optimisation less complicated, and the result easier to understand. All formulas are calculated for all the 50 farms included in the model. Formulas for each calculation for general information, all three alternatives, and the connected cells directly in the model are presented in the tables below.

Table 8 Formulas for calculations in general information

Formula	**Explanation**
CM_l* Dp_l	Total amount of drymatter in manure from cattle from a farm (ton)

PM_l* Dp_l	Total amount of drymatter in manure from pigs from a farm (ton)
(Dp_l* $BiopC_l$* CM_l) + (Dp_l* $BiopP_l$* PM_l)	This formula calculates the maximum biogaspotential the farm (Nm^3)

Table 9 Formulas for calculations done for Alternative 1

Formula	**Explanation**
(CM_l* EmC_i) + (PM_l* EmP_i)	Total amount of GHG emission from storage of manure at a farm (kg CO_2 – equivalents). Abbreviated to $TEsm_i$
((nDc_l+nSc_l+nOc_l)* EnC_l)+((nBp_l+nSp_l)* EnP_l)	Total demand for heat at each farm (kWh). Given the abbreviation "TdE_i".
TdE* Elp_l	The total cost for the electricity used to meet the energy demand (NOK). Abbreviated to $TcEl_i$
TdE* Wcp_l	Total cost for the woodchips used to meet the energy demand (NOK) TcW_i
TdE***** $EmEl_i$	The total emission from utilizing electricity to meet the energy demand $TeEl_i$

Table 10 Formulas for calculations done for Alternative 2

Formula	**Explanation**
(CM_l+ PM_l)/ CaM_j	Percentage of the manure produced at the farm that can be utilized into the Telemarksreaktor. Abbreviated to PMu_j
(Dp_l* $BiopC_l$* CM_l) + (Dp_l* $BiopP_l$* PM_l)* OET_j* PMu_j	Potential biogas production from the Telemarksreaktor (Nm^3). Abbreviated to PBP_j
PBP_j * Epo_l *EHP_j	Energy produced from the biogas (kWh). Abbreviated to EPB_j.
TdE_i / EPB_j.	Energy to spare/needed extra energy to fill the demand (kWh). Abbreviated to ESN_j
ESN_j* Elp_l	Cost of needed extra energy supplied from electricity (NOK). Abbreviated to CNE_j.
ESN_j* Wcp_l	Cost of needed extra energy supplied from woodchips (NOK). Abbriviated to CNW_j

ESN_j* $EmEl_i$	Emissions from utilization of electricity to supply the extra needed energy (kg CO_2-equivalents). Abbreviated to EEE_j
($ECrEl_j$ * CM_l)+($EPrEl_j$* PM_l)* PMu_j	Total emissions from manure when replacing electricity (kg CO_2-equivalents). Abbreviated to EME_j
($ECrW_j$ * CM_l)+($EPrW_j$* PM_l)* PMu_j	Total emissions from manure when replacing woodchips (kg CO_2-equivalents). Abbreviated to EMW_j
(($GsDc_j$* nDc_l)+ ($GsSc_j$* nSc_l)+ ($GsOc_j$* nOc_l)+(($GsBp_j$* nBp_l)+ ($GsSp_j$* nSp_l))* PMu_j	Total Governmental support for biogasproduction in Alternative 2 (NOK). Abbreviated to TGSA2
Using the NPV function in Excel: ($IntR_j$;calculations for cost each year)+(- InC_j*(1/ InS_j)	Net present value for the Telemarksreaktor. Abbreviated to $NPVA2_j$
Using the AVDRAG function in Excel: ($IntR_j$; LE_j; $NPVA2_j$)*(-1)	Yearly cost/income from biogas production from the Telemarksreaktor. Abbreviated to $YCbp_j$

Table 11 Formulas used for calculations for Alternative 3

Formula	**Explanation**
(DFG_k*EfT_k*(CM_l+ PM_l))*2	GHG emissions from transport to and from GreVe biogass (kg CO_2-equivalents). Abbreviated to $ETGb_k$
(CM_l* $ErFC_k$) + (PM_l* $ErFP_k$)	GHG emissions from biogas replacing diesel (kg CO_2-equivalents). Abbreviated to $EBrD_k$
(Dp_l* GsM_k * CM_l) + (Dp_l* GsM_k * PM_l)*0,33	Governmental support for manure delivered to GreVe biogass (NOK). Abbreviated to $GsmGb_k$
TdE* Elp_l	GHG emissions from utilizing electricity to meet the energy demand on the farm (kg CO_2-equivalents). Abbreviated to $EuElf_k$
TdE* Wcp_l	Costs for utilization of electricity to meet the energy demand on the farm (NOK). Abbreviated to $CuElf_k$
TdE***** $EmEl_i$	Costs for utilization of woodchips to meet the energy demand on the farm (NOK). Abbreviated to $CuWf_k$

Table 12 Formulas used for calculations in the Biogas model

Formula	Explanation
$(TcEl_i * X_{1\text{-}50i})+((YCbp_j + CNE_j) * Y_{1\text{-}50j}+((GsmGb_k + CuElf_k) * Z_{1\text{-}50k})$	Sum of all costs after a solution is calculated with the electricity scenario (NOK).
$(TcW_i * X_{1\text{-}50i})+((YCbp_j + CNW_j) * Y_{1\text{-}50j})+((GsmGb_k + CuWf_k) * Z_{1\text{-}50k})$	Sum of all costs after a solution is calculated with the woodchip-scenario (NOK).
$((TEsm_i+TeEl_i) * X_{1\text{-}50i})+((EME_j + EEE_j) * Y_{1\text{-}50j})+((ETGb_k + EBrD_k + EuElf_k) * Z_{1\text{-}50k})$	Sum of all emissions after a solution is calculated with the electricity scenario (kg CO_2-equivalents).
$((TEsm_i+TeW_i) * X_{1\text{-}50i})+((EMW_j) * Y_{1\text{-}50j})+((ETGb_k + EBrD_k) * Z_{1\text{-}50k})$	Sum of all emissions after a solution is calculated with the woodchip scenario (kg CO_2-equivalents).
1*((sum emission-targetvalue emission)*(1/targetvalue emission))	The weighted deviation for GHG emissions. Abbreviated to WdevE
1*((sum cost-targetvalue cost)*(1/targetvalue cost))	The weighted deviation for GHG emissions. Abbreviated to WdevC
Using the MAXA function in Excel (WdevE; WdevC)	Minimizing the maximum deviation. Abbreviated to MMD

7.5 Constraints

The constraints in a model sets the framework for the model's possible solutions. The model has some absolute constraints, for instant that the variable cells must be binary. These constraints are programmed with an "equal to" symbol that insists that the variable must be equal. Other constraints are flexible, which means that they do not give the variable cells exact numbers to fill, but allows the model to choose any number under or over a given maximum or minimum. These constraints are balanced with an "equal to or bigger" symbol or "equal to or less" symbol. The constraints are comprised of the variables and some parameters.They are all described in Table 8 below.

Equation	Explanation
$X_{1\text{-}50i}$ = binary	This is the binary constraint for the variable of Alternative 1
$Y_{1\text{-}50j}$ = binary	This is the binary constraint for the variable of Alternative 2
$Z_{1\text{-}50k}$ = binary	This is the binary constraint for the variable of Alternative 3
$\sum X_{1\text{-}50i}, Y_{1\text{-}50j}, Z_{1\text{-}50k} = 1$	This constraint ensures that the model must choose one, and only one, of the alternatives.
WdevE ≤ MMD	The weighted deviation for GHG emissions cannot be bigger than the minimized maximum deviation
WdevC≤ MMD	The weighted deviation for GHG costs cannot be bigger than the minimized maximum deviation

7.6 Objective functions

The two goals in this MOILP-model are to minimize the emission of GHG emissions from the 50 farms included in the model, and to minimise the costs for the same farms. These objective functions are formulated mathematically as the sum of each cost for each alternative, and each emission factor for each alternative. The objective function for the minimization of emissions is formulated mathematically as:

min: $\sum_{a=1}^{50}(\text{X}1 - 50\text{i} * (\text{TEsm}_i + \text{TeEl}_i))\text{a}+(\text{Y}_{1\text{-}50\text{j}}*(\text{EME}_j+ \text{EEE}_j+ \text{EMW}_j))\text{a}+(\text{Z}_{1\text{-}50k}*(\text{ETGb}_k+ \text{EBrD}_k+ \text{EuElf}_k))\text{a}$

All the parameters stated in this objective function is stated above in this chapter, and described in detail in chapter 5.

The objective function for the minimisation of costs is formulated mathematically as:

min: $\sum_{a=1}^{50}(\text{X}1 - 50\text{i} * (\text{TcEl}_i+ \text{TcW}_i))\text{a}+ (\text{Y}_{1\text{-}50\text{j}}*(\text{YCbp}_j+ \text{CNE}_{j.}+ \text{CNW}_j))\text{a}+(\text{Z}_{1\text{-}50k}*(\text{GsmGb}_k+ \text{CuElf}_k+ \text{CuWlf}_k))\text{a}$

As with the objective function for minimising emissions, the variables and parameters are presented above in this chapter, and further described in chapter 5.

The two objective functions are solved by themselves in Solver to obtain the potential of minimised costs and emissions before combining them. The values obtained from this method is considered goal-values (GV1 and GV2) when the model is solved for the main objective function.

The main objective function in this MOILP-model is programmed to minimise the maximum deviation between the two objective functions for minimised emissions and costs. It is formulated mathematically as:

Min: Q

Subject to:

$$V1\left(\frac{\sum_{a=1}^{50}(\mathrm{X1{-}50i}*(\mathrm{TEsm}i + \mathrm{TeEl}i))\mathrm{a}+(\mathrm{Y1{-}50j}*(\mathrm{EME}j+\mathrm{EEE}j+\mathrm{EMW}j))\mathrm{a}+(\mathrm{Z1{-}50}k*(\mathrm{ETGb}k+\mathrm{EBrD}k+\mathrm{EuElf}k))\mathrm{a}}{GV1}\right) \leq Q$$

$$V2\left(\frac{\sum_{a=1}^{50}(\mathrm{X1{-}50i}*(\mathrm{TcEl}i+\mathrm{TcW}i))\mathrm{a}+(\mathrm{Y1{-}50j}*(\mathrm{YCbp}j+\mathrm{CNE}j.+\mathrm{CNW}j))\mathrm{a}+(\mathrm{Z1{-}50}k*(\mathrm{GsmGb}k+\mathrm{CuElf}k+\mathrm{CuWlf}k))\mathrm{a}}{GV2}\right) \leq Q$$

Where Q is the maximum deviation from the goal-values, V1 is the weight given to the emission goal, V2 is the weight value given to the cost goal. The objective function is solved as a percentage and shows the maximum value of the percentage deviation from the goal-values.

The weight values, V1 and V2, are set as the price for CO_2-quotas in the representation year 2015, established by the Environmental Agency in Norway.

8 Results

8.1 Initial results

Based on the stated assumptions, calculations, and available data, the model has provided initial solutions to minimize the possible costs and GHG emissions of the chosen farms in Vestfold for the two scenarios. The numbers are a product of all available data considering the two objective functions included in the model. Costs and GHG emissions on the farm from fractions not considered compatible with biogas production, for instant GHG emissions from tractor or operating costs from the whole farm, must be added by the farm in addition to the data from the model. A representation of the initial results for both scenarios are presented in Attachment 2 and 3.

The result for the model when it was solved for farms using electricity to meet their demand for heat at their barn or to heat water was: zero farms chose Alternative 1, six farms chose Alternative 2, and the remaining 44 farms chose Alternative 3. The model's result when it was solved for all farms using woodchips as fuel to meet the demand for energy at the farm was: zero farms chose Alternative 1, 19 farms chose Alternative 2, and 31 farms chose Alternative 3. The model as programmed in Excel is presented in attachment 1 and 2. The result from GHG emissions and costs are shown in the figures below.

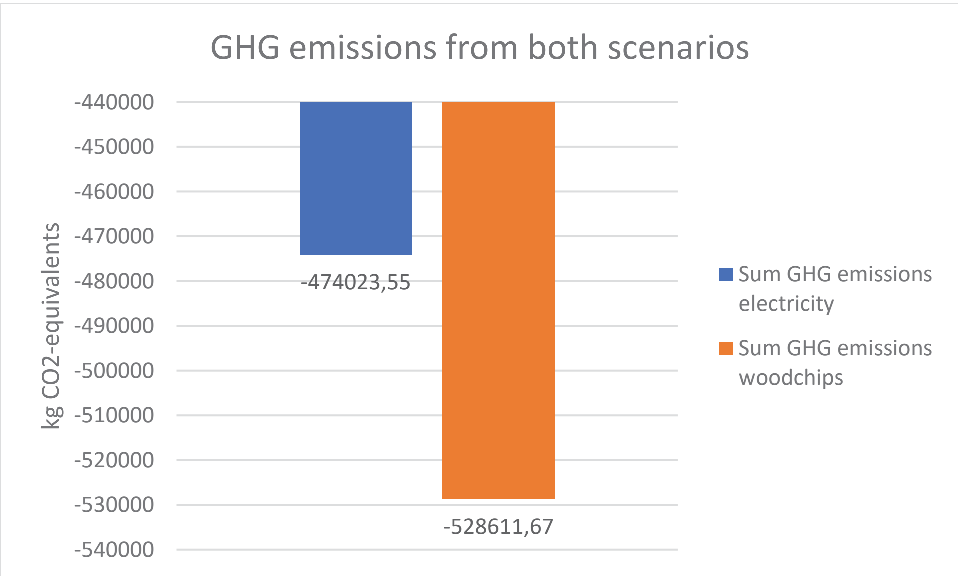


Figure 3 Total amount of GHG emissions for both scenarios

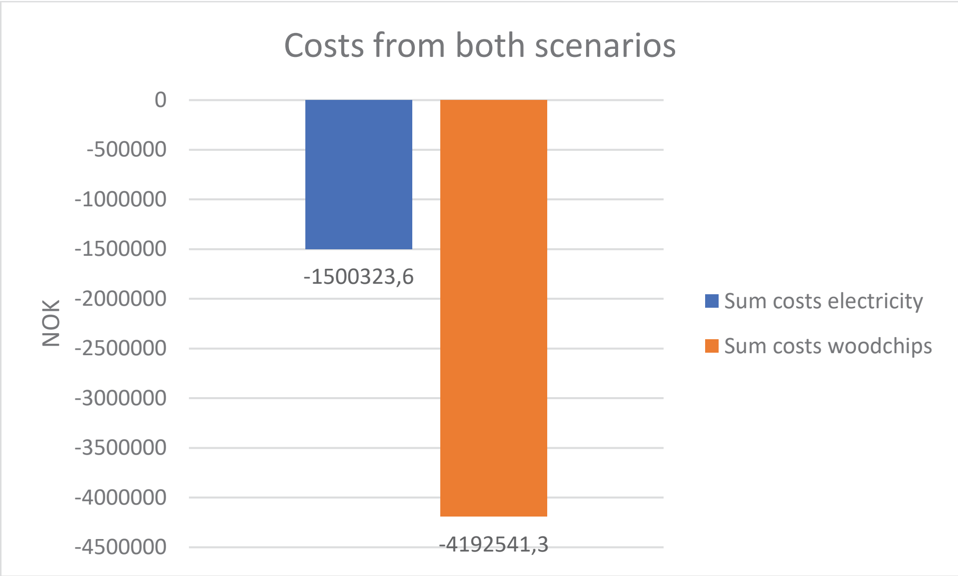


Figure 4 Total amount of costs for both scenarios

As shown in figures 3 and 4 the numbers are all negative. What figure 3 presents for the model' solved total GHG emissions is that the different scenarios with electricity or woodchips as energy carrier has a negative result on the total GHG emissions. This means that the net GHG emissions from all the choices made for the 50 farms have the potential to save 461,6 tons CO_2-equivalents for the scenario with utilisation of electricity, and 1186,6 tons CO_2-equivalents for the scenario with utilisation of woodchips, should all the farms execute the models choice.

Figure 4 presents the model's optimal solution for costs, this too has a negative result. This mean that the numbers for both scenarios is a total net income for all the farms. This total net income for the electricity scenario was 1 969 277 NOK, and the total net income for the woodchips scenario was 539 144 NOK.

The total GHG emissions and total costs are a product form the choices made by the model. The total GHG emissions and costs from each alterative is presented graphically in figures below with one figure for each scenario.

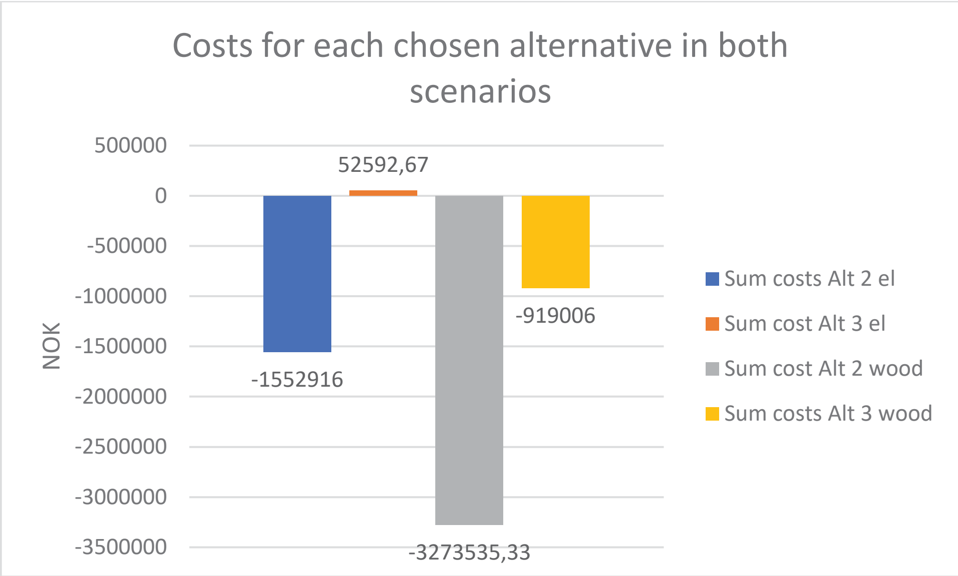


Figure 5 Total costs for each chosen alternative for both scenarios

Figure 5 presents all the summarised costs for both alternatives. There are three negative alternatives, which indicates that they are incomes and not costs, and one alternative that is positive. These numbers are a summary of all the individual costs and incomes at the individual farms, and the difference between the alternatives and scenarios are high. The reason for the large negative costs is because they are a product of all the governmental supports the farms receive from participating in production of biogas. The summary of Alternative 3 in the scenario for electricity has an actual cost. This is because the weight value for GHG emissions is greater than cost, and the model chose the solution with the lowest possible emission of GHG's.

The total summarised number for GHG emissions for each alternative in both scenarios are presented graphically the same way as costs in the figure below.

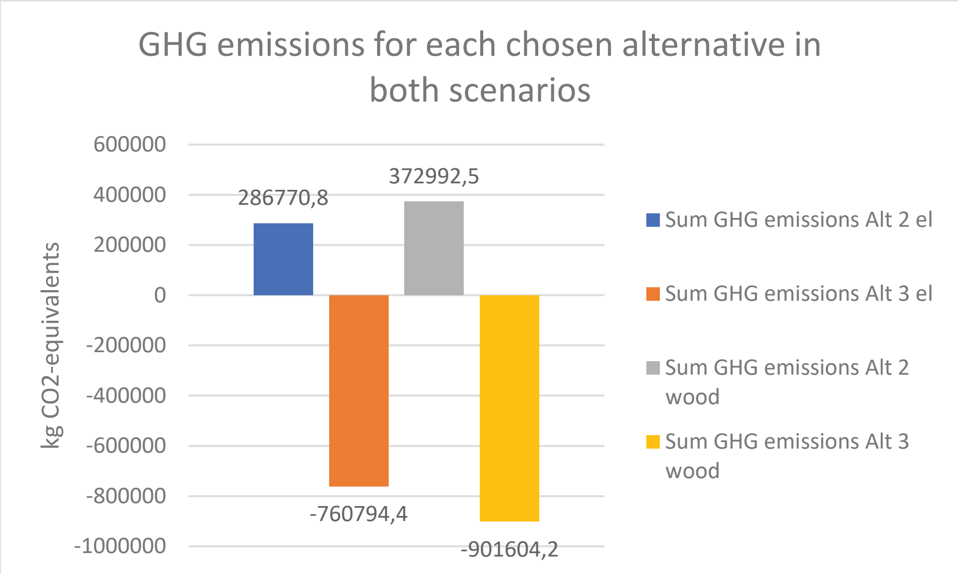


Figure 6 Total GHG emissions for each alternative for both scenarios

The result shown in figure 6 is that all farms that chooses Alternative 2, in both scenarios, will end up contributing to producing and releasing GHG emissions. This is because of the calculated emissions from Alternative 2, from spreading of the manure and the production of biogas. The farms that chose Alternative 3 in both scenarios will contribute to a reduction of GHG emissions. This is because the biogas and biomethane produced at GreVe biogass replaces fossil fuels, and that has a greater reduction potential than what the biogas produced locally at the farm replaces. There are more farms that chose Alternative 3 in both scenarios, and the total GHG emissions from the 50 farms will be negative when the two alternatives are summarised.

The total emissions for Alternative 1, where the farm does not invest in production of biogas, was calculated to compare the emissions the 50 farms have without any investment in biogas production. The model's solution, for either scenario, shows a considerable difference in the amount of emitted kg CO_2-equivalents. This is presented graphically in figure 7.

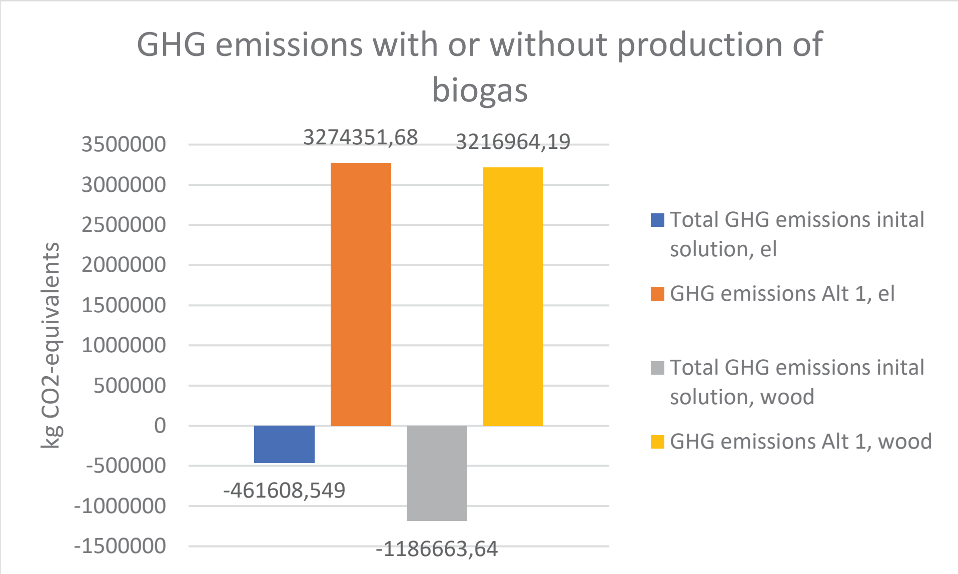


Figure 7 Comparing potential GHG emissions

Figure 7 presents the calculated amount of GHG emissions produced if no farms choose to produce biogas (Alt 1). Should the resulting choices from the model, in both scenarios, be implemented, Vestfold would see a considerable decrease in GHG emissions from its agriculture.

The main objective function ended up at 1,5 % for the electricity scenario and at 55% for the woodchips scenario. The result shows that the maximum deviation from the calculated goal values in the electricity-scenario is very low and that the model found a good solution to find the minimum maximum deviation. The deviation in the woodchip-scenario is substantial. The deviation is found in the goal value for GHG emission. The model has chosen a solution that deviates 55% from what the model would look like if it had only been optimised for GHG emissions, without considering costs.

The initial solution is summarised in the table below, with number of farms at each alternative, total cost, and total GHG emissions for both scenarios.

Table 13 The initial solution to the biogas model

Alternative/scenario	Number of farms	GHG-emissions (kg CO_2-equivalents)	Costs (NOK)
Alt 1/electricity	0	0	0
Alt 2/electricity	6	286770	-1552416
Alt 3/electricity	44	-760794,4	52592,6
Sum electricity	50	-474023,6	-1500323,6

Alt 1/woodchips	0	0	0
Alt 2/woodchips	19	372992,5	-3273535,3
Alt 3/woodchips	31	-901604,2	-919006
Sum woodchips	50	-528611,6	-4192541,3

The numbers show that the farms have a huge potential for reducing GHG-emissions and potential for increased incomes at their farm, should they collectively decide to implement the solution at the farm.

8.2 Sensitivity analysis

The Excel Solver function usually provides a sensitivity report when it has provided an optimal solution for linear problems, but that report is compromised when using the minimise the maximum deviation function. By using a MOILP- model, and therefore having multiple objectives, the rapport from Solver will only give answers to the compounded values for both objectives. But a sensitivity analysis should be executed for the most uncertain data to check how much the optimal solution will change for each scenario and an increase or decrease in the uncertain values. As presented in chapter 5, the demand for energy at the farms is very uncertain. The model has therefore been solved for an increase or decrease of 50% in the farms demand for energy. The other value that will be analysed is the distances from GreVe biogass. The distance from GreVe biogass could be a crucial factor when finding the optimal solution to the MOILP-model, and the model has therefore been solved for a 50% and a 100% increase in the distance from farms to GreVe.

8.2.1 Sensitivity in demand for energy

The demand for energy at the farm is calculated from the energy demand for heating each of the farm’s animals have. The uncertainties around these values were mentioned and explained in chapter 5. As mentioned, these numbers are found either outside of Norway or calculated from a small pool of farms. There is therefore cause to perform a sensitivity analysis to check how robust the initial solution is to changes in a value that is as uncertain as this. Chosen values for the sensitivity analysis was 50% up or down of the demand for energy for pigs and cattle. The new values, when they have been reduced by 50%, are 894,75 kWh per unit of cattle and 4,2 kWh per unit pigs, and 2684,2 kWh per unit cattle and 12,6 kWh per unit pig when the original numbers are increased by 50%.

The new values were plotted into the model, and the model was solved again, for both the electricity and the woodchip scenario. The high-demand scenario for electricity was not possible to solve because the linear demands for Solver was not met, and because of the limited amount of time, the problems were not explored further. The solution for 50% decreases energy demand in the electricity scenario was nine farms choosing Alternative 2 and 41 farmers choosing Alternative 3. This means that three farms changed their optimal choice when faced with less demand for energy on the farm. For both increase and decrease of 50% in energy demand for the woodchips scenario, the optimal solution for all 50 farms was to choose Alternative 3. The result for GHG emissions and costs for the other scenarios are presented in figure 8 (GHG emissions) and figure 9 (costs).

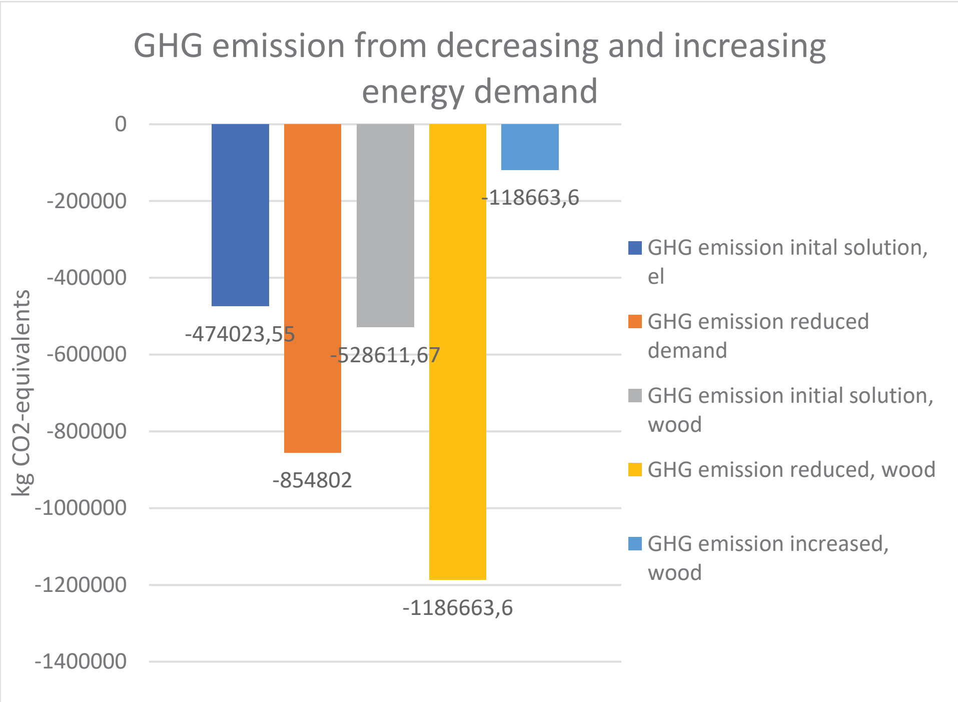


Figure 8 GHG emission from decreasing and increasing energy demand

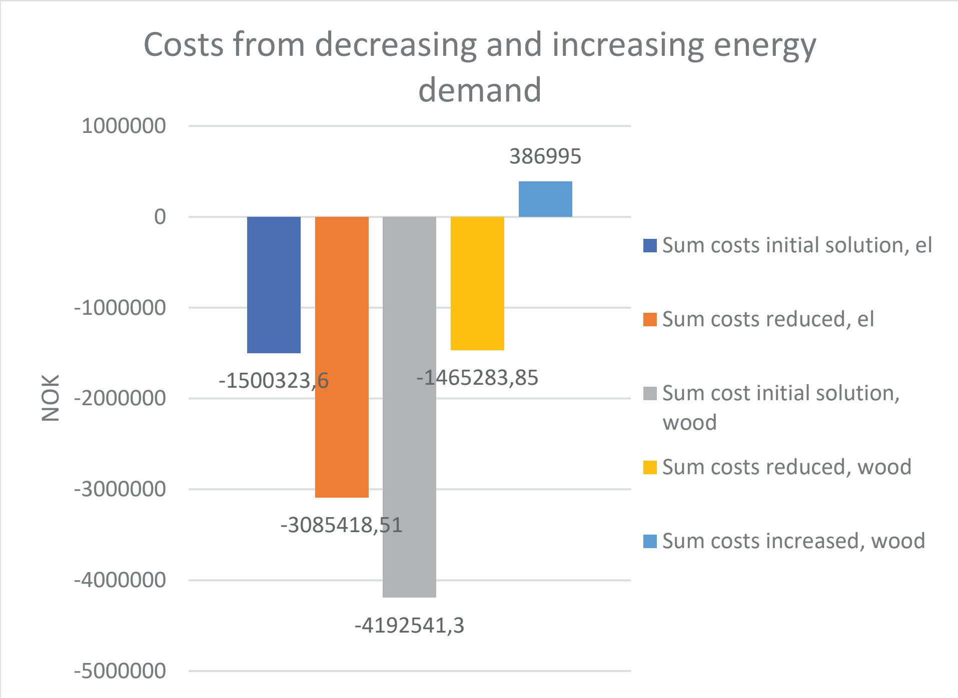


Figure 9 Costs from decreasing and increasing energy demand

The result from the new solutions shows that the initial result is very sensitive for changes in the energy demand on each individual farm. These results are accumulated numbers for all the 50 individual farms, but the changes are still significant, especially for increased demand. This means that the energy demand on the farm must be accurate to get the most accurate solution from this model.

8.2.2 Sensitivity for distance

The limits of the distance the manure and biofertilizer must be transported is a research question, and will therefore be analysed for sensitivity. This sensitivity analysis will only study how many farms chooses differently with different distances, and not focus on the GHG emissions and costs. The farms that chose to have their own reactor, and not to send their manure to GreVe biogass, in both scenarios was mostly driven by their potential income from governmental support. Most of the farms have large differences between their potential income in Alternative 2 and Alternative 3, and the model chose the alternative where the farms emissions and income got at a Pareto-optimal solution. This sensitivity analysis will present how much the distances will change the initial result, and if there is a limit to transport. The model will therefore be solved for an increase in distance of 50% and 100%.

The new optimal solutions for the increased and decreased distances gave all new solutions to the model. When solving the model with a 50% increase in distance in the electricity scenario, only one farm changed its optimal choice. The result was that seven farms chose Alternative 2 and 43 chose Alternative 3. When the distance for all farms was increased by 100%, the model could not be solved, because it did not meet the linearity demands. Because of limited time, this problem was not studied further. When distance was increased in the woodchip scenario, both 50% and 100% the optimal solution was that all 50 farms should send their manure to GreVe biogas. This indicates that some of the calculations of the initial solution might be wrong.

9 Discussion

9.1 Uncertainties in the datasets and calculations

An optimisation model can, as mentioned in chapter 6, give valuable insight to complex problems and be used as a decision-making tool, but the results must be interpreted as a product of the data obtained for the data base, assumptions, uncertainties, and way the model simplifies reality. From the research, the programmed model, and the results, we can see that the data for energy demand, the potential production of biogas from manure, and the calculations for annual costs might be the most uncertain. This subchapter will focus on these factors.

As mentioned in chapter 5, the data for energy demand on each farm was very difficult to find. It was assumed that the English climate and technological development is closely related to the Norwegian, so an energy demand per pig was obtained from English data. Even with the similarities between England and Norway, these data are not certain enough to say for certain if the demand for energy is calculated correctly. The demand may differ from the actual demand. The energy demand for cattle has the same problem. It was calculated from data from one farm in Norway, then quality assured from more calculations from the overall costs for energy at multiple cattle-farms. The demand for energy will differ between different farms, and the number is uncertain because of this. The calculations may also be wrong. Furthermore, it is assumed that all the different types of cattle and pigs are demanding the same amount of energy. A breeding pig might need more heating than a pig for slaughter. This need to be explored more, and as the sensitivity report shows, the initial solution is sensitive for changes in the overall demand. A shift in the demand for energy will have consequences for the overall costs and GHG emissions. The model might have a completely different solution should the numbers shift significantly.

The next assumed data that must be discussed is the assumed capacity for the Telemarksreaktor. It is assumed n the thesis that the reactor can take 2840 m^3 annually. This is based on the data received from Rune Bakke, and an assumption that 1 ton manure equals $1m^2$. Should this number shift, the potential production of biogas would shift, and result in a new optimal solution. This would also cause a change in the potential produced energy, as well as the governmental support, because of the amount manure going to production of biogas.

As discussed a little already, he model is a product of a data base and several calculations. If the calculations are wrong, the result may be wrong. Many of the calculations are standard math, but human error should never be ruled out. The calculation for NPV and the farms annual costs for the Telemarksreaktor was calculated by using the data obtained for the economy of Alternative 2. Some farms had a significant annual income from producing biogas locally. Some farms could profit over 100 000 NOK annually. This is calculated mostly from the annual support the farm gets. The support-numbers were thoroughly discussed, and found to be sound. This gaps in profit for different farms will affect the result of the model. Even if the calculations were done through Excel and multiple times, there might be an error there.

To make the model more robust, more thorough mapping of the discussed data should be executed. Individual farmers could contribute with much more accurate data, and could give a more accurate result. Much of the uncertainty in the model would be solved if the demand for energy was accurate.

9.2 Choice of software

As presented in chapter 6, the choice of software to solve this multiple objective analysis was Excel Solver. Like all other software, it comes with its own strengths and weaknesses. The weaknesses of Solver are its limited number of variables possible to solve for and the simple structure in the software. Solver can only solve for 200 variables; this means that the model that is constructed for this thesis, with three different alternative choices, can only produce an optimal solution for 66 farms at a time. This means that wherever the model might be used, it can only solve the problem for a maximum of 66 farms, regardless of how many farms there might be in the chosen area, county, or country. More farms could be solved for if the model was programmed with a more complex and sophisticated software, like for instant GAMS. More multiple objectives could also be explored with a more complex software than Excel Solver, for instance the farms attitudes towards biogas. This would give the model a bigger pool of farms to choose from, and maybe a more realistic result. The strength of programming the model in Excel is that the software is its availability. Everyone with Microsoft Office has access to Excel Solver, and can, through some studying, understand the method because the interface is known.

9.3 Realistic implementation

This models result is a product of the optimal choices for two factors and goals. The result is only applicable if the 50 farms included in the model makes the decision the model told them to do. Because of the simplicity of the model, the attitudes the farms have for production of biogas was not included. All the different farms have different goals, values, and ways of life. The resulting choice from the model, might be something the farm does not want to participate in, regardless of the potential increased income and reduction of GHG emissions. If one farm should choose not to follow the recommended choice from the model, the result would be different and the optimal solution might be different for the rest of the farms. The outcome might also be different if we factor in attitude in the model, all have different goals, values, way of life. All need to make the choice the model tells them to for this outcome to become a reality. The human values and attitude towards production of biogas was not implemented as a factor in the model, and the result from the model must therefore be considered as more a theoretical result than a realistic one. The optimal solution might be different if we factor in the farms attitude towards production of biogas.

10 Conclusion

This work done in this thesis has shown that it is possible to program a model that can solve for an optimal solution to a multiple objective integer linear problem considering biogas production in agriculture. It has shown that, if the model is correct, the potential for reduction of GHG emissions in agriculture can be reduced significantly compared to the reference scenario where there is no production of biogas from the farm's produced manure. The optimal solution will also have a positive result on the farm's economy, which should be a strong indicator that production of biogas is something each individual farm should seriously consider participating in the production of biogas. Some farms might even make a large profit because of the governmental subsidies they would receive.

The limit for transport was analysed and found that there is little sensitivity connected to this factor. The GHG emissions from the activity is small compared to the potential for reduced GHG emissions by choosing Alternative 3. As discussed in chapter 9, the specific amounts of times the transport to and from GreVe, is not calculated, but rather the emissions for transporting the total amount of manure. The number and limitations might be different should the transport emissions be altered.

When the model chose Alternative 2 for the farms, regardless of the scenario, the farms were the ones that had the highest annual income. These were the farms where the primary livestock was cattle, because the difference between amount of governmental support can be 400% per unit cattle and per unit pig. Another observation is that the farms with cattle has a much higher demand for energy that pig per unit, and the cost for energy at the farm is much higher when the livestock is primarily cattle.

GHG emissions resulting from each result in the two different scenarios was significantly less reduced than the total GHG emissions from Alternative 1, should the farms choose to not participate in production of biogas. This is because the production of biogas saves CO_2-equivalents, whether it be from better storage and replacement of energy carrier at the farm, or replacing energy carrier for vehicles. Production of biogas will always have a positive result on reducing GHG emission.

The constructed model gave an insight into the optimal choices for a given number of farms in a given area, but it looks like the model should be able to transfer easily to different areas, by editing the data base to fit the new area and farms. But before the model is taken seriously, the data should be quality assured and processed.

11 Further research

This thesis is going to be implemented in Kari-Anne Lyng's Phd and the BioValueChain project at Østfoldforskning. The thesis will therefore be processed and the data be quality assured. More sensitivity analysis should be done for more of the data base and the calculations implemented in the model. Hopefully they will have access to concrete data of the specific energy demands at the farm.

As discussed, the Excel Solver is a simplistic model that is readily available to the public. It would be especially interesting to develop this model in a more complex software, like GAMS, to possibly solve for more goals, like the farms attitude towards biogas production, and more farms, possibly all farms in Vestfold county or other areas that has the same decision-making problem. It's not certain that the model programmed in GAMS is going to be better, but it might bring in more complexity, and give further insight into the realistic choises for each individual farm.

Lastly, should the model be used in different areas than Vestfold, the data base must be changed. New data for each individual new farm must be found and registered into the model before it can give a result with any meaning to the area. From these changes in data base, the model should be programmed to do all the necessary calculations itself, and give a transparent and documented result for all new farms implemented in the model. The model will then solve for the optimal solution, and give insight to a possible profitable and environmental friendly solution to the question of how to best handle farm produced manure to minimize GHG emissions for a sustainable future.

12 References

Andersen, A., Asphjell, T., Birkeli, K., Flugsrud, K., Frigstad, H., Gade, H. & Økstad, E. (2015). *Klimatiltak og utslippsbaner mot 2030 - Kunnskapsgrunnlag for lavutslippsutvikling* (M-386). Retrieved from http://www.miljodirektoratet.no/Documents/publikasjoner/M386/M386.pdf

Fiksen, K., Harsem, S., Lossius, T., & Magnus, E. (2016). *Verdiskaping fra produksjon av biogass på Østlandet* (7/2016). Retrieved from http://www.avfallnorge.no/pop.cfm?FuseAction=Doc&pAction=View&pDocumentId=70356

Forskrift om tilskudd for levering av husdyrgjødsel til biogassanlegg. (2015). *Forskrift om tilskudd for levering av husdyrgjødsel til biogassanlegg*. Retrieved from https://lovdata.no/dokument/SF/forskrift/2014-12-19-1815?q=biogass.

Fylstra, D., Lasdon, L., Watson, J., & Waren, A. (1998). Design and use of the Microsoft Excel Solver. *Interfaces*, *28*(5), 29-55.

Grønn varme i landbruket, energiråd innlandet. (2014). Gårdsvarmeanlegg – noe for deg? [Brochure]. Flisa: Grønn varme i landbruket.

Hengeveld, E. J., Bekkering, J., van Gemert, W. J. T., & Broekhuis, A. A. (2016). Biogas infrastructures from farm to regional scale, prospects of biogas transport grids. *Biomass and Bioenergy, 86,* 43-52. doi:http://dx.doi.org/10.1016/j.biombioe.2016.01.005

Karlengen, I. J., Svihus, B., Kjos, N. P., & Harstad, O. M. (2012). *Husdyrgjødsel; oppdatering avmengder gjødsel og utskillelse av nitrogen, forsfor og kalium – Sluttrapport* (17.12.2012). Retrieved from https://www.landbruksdirektoratet.no/no/dokumenter/publikasjoner/husdyrgj%C3%B8dsel-oppdatering-av-mengder-gj%C3%B8dsel-og-utskillelse-av-nitrogen-fosfor-og-kalium.sluttrapport-umb

Larsen, H. N. (2016, 03.02). Norsk strøm blir renere. Retrieved from https://www.asplanviak.no/aktuelt/2016/02/03/nordisk-stroem-blir-renere/

Lyng, K. A., Modahl, I. S., Moller, H., Morken, J., Briseid, T., & Hanssen, O. J. (2015). The BioValueChain model: a Norwegian model for calculating environmental impacts of biogas value chains. *International Journal of Life Cycle Assessment, 20*(4), 490-502. doi:10.1007/s11367-015-0851-5

Lånke, A. F., Berg, H. Ø., Melbye, A. M., Helland, L., & Solberg, F. E. (2016). *Markedsrapport: Biogass i oslofjord-regionen* (1350014474). Retrieved from https://www.biogas2020.se/wp-content/uploads/2016/05/markedsrapport-biogass-oslofjordregionen-ramblll-endelig-003.pdf

MacDonald, Z. (1995). Teaching linear programming using Microsoft Excel Solver. *Computers in Higher Education Economics Review, 9*(3).

Morken, J., Fjorttoft, C., & Briseid, T. (2015). Agricultural biogas plants-energy balance. In *Proceedings of the 25th NJF Congress. Nordic View To Sustainable Rural Development. Riga: NJF Latvia* (pp. 370-374).

Paris agreement. (2015). *Paris Agreement*. Retrieved from http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf

Raadal, H. L., Schakenda, V., & Morken, J. (2008). *Potensialstudie for biogass i Norge* (OR 21.08). Retrieved from http://www.biogassostfold.org/wp-content/uploads/Potensialstudie-for-biogass-i-Norge.pdf

Regjeringen.no. (2016, 21.06). Norge har ratifisert Parisavtalen. Retrieved from https://www.regjeringen.no/no/aktuelt/norge-har-ratifisert-parisavtalen/id2505365/

Modahl, I. S., Lyng, K.-A., Baxter, J., Bakke, R., & Hovland, J. (2014). *Utilisation of farm manure for biogas production environmental and economic analysis of local and central biogas plants, including pipeline transport of biogas* (OR.06.04) Retrieved from https://www.ostfoldforskning.no/media/1080/716-1.pdf

Silva, S., Alcada-Almeida, L., & Dias, L. C. (2017). Multiobjective programming for sizing and locating biogas plants: A model and an application in a region of Portugal. *Computers & Operations Research*, *83*, 189-198. doi:10.1016/j.cor.2017.02.016

SSB. (2016). Utslipp av klimagasser, endelige tall. Retrieved from https://www.ssb.no/natur-og-miljo/statistikker/klimagassn/aar-endelige

Meld. St. 39 (2008-2009). *Klimautfordringene - landbruket en del av løsningen*. Retrieved from https://www.regjeringen.no/contentassets/1e463879f8fd48ca8acc2e6b4bceac52/no/pdfs/stm200820090039000dddpdfs.pdf

Sundtoft, T. (2014). *Nasjonal tverrsektoriell biogasstrategi* (T-1545). Retrieved from https://www.regjeringen.no/contentassets/255fa489d18d46feb3f8237bc5c096f0/t-1545.pdf

Taylor, B. W. (2016). *Introduction to management science* (12. ed.). Viginia Polytechnic Institute ans State Univercity: Pearson.

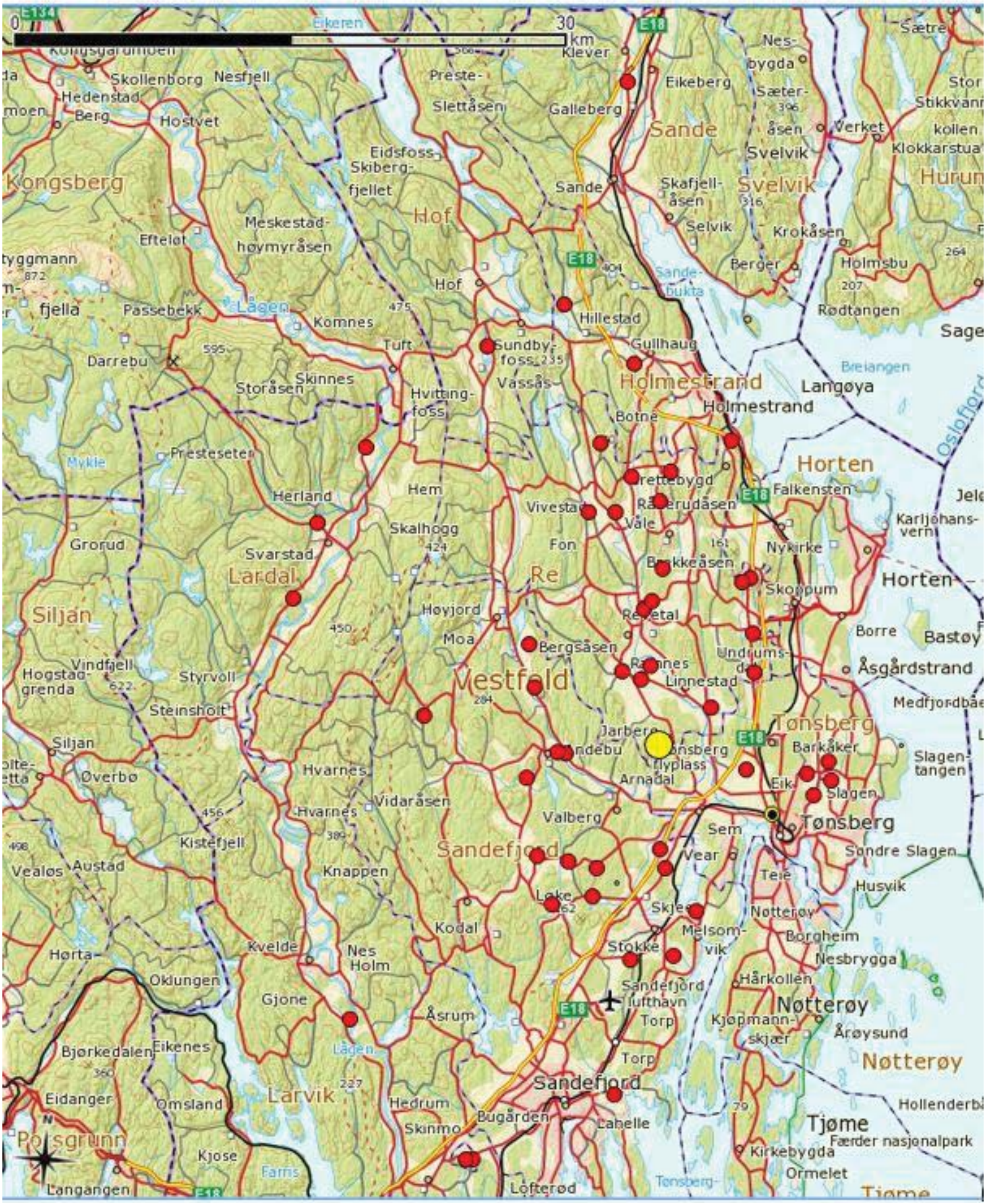
TheCarbonTrust. (2016). *Energy use in pig farming*. Retrieved from http://pork.ahdb.org.uk/media/39721/energy_use_in_pig_farms_carbon_trust.pdf

Vestfold fylkeskommune. (2015). *Regional plan for klima og energi, 2016-2020*. Vestfold fylkeskommune. Retrieved from https://www.vfk.no/Documents/vfk.no-dok/Milj%C3%B8%20og%20klima/Regional%20plan%20for%20klima%20og%20energi/Vfk_Regional_Plan_aug_2016_korr_02.pdf

Woll, T. (2016, 24.10). Takk for maten, jeg kjører på biogass. Retrieved from http://energigass.no/takk-for-maten-jeg-kjorer-pa-biogass/

Attachment 1

A visual of locations of the farms included in the model made with GIS. The red dots represent the included farms, and the yellow dot represents GreVe biogass.



Attachment 2

The model with the initial solution for electricity

Binary-model

Objective Costs			**Objective Emissions**		
Costs for Alt 1	0,00	NOK/year	CO2 equivalents Alt1	0	kg CO2-eq/year
Costs for Alt 2	-1552916,27	NOK/year	CO2 equivalents Alt2	286770,8884	kg CO2-eq/year
Costs for Alt 3	52592,67173	NOK/year	CO2 equivalents Alt3	-760794,4354	kg CO2-eq/year
SUM Costs	-1500323,60	NOK/year	Sum Emissions	-474023,547	kg CO2-eq/year
Target Value	-3729077,18	NOK/year	Target Value	-481497,931	kg CO2-eq/year

Objective function	Weight value	Weighed deviation		Max deviation
Deviation emissions	1	0,01552319	≤	0,0155232
Deviation costs	0,02	0,011564801	≤	0,0155232
MINIMIZE MAXIMUM DEVIATION		0,01552319		

Decision variables | Choice-constraint

Alternative 1	cost	CO2-eq emitted		Alternative 2	Costs	CO2-eq emitted		Alternative 3	Costs	CO2-eq emitted		sum		
0	6577,97	128644,06		0	-79771,833	16472,00		1	-70034,827	- 71007,74		1	≤	1
0	5054,31	109892,17		0	-58574,837	16472,00		1	-60470,486	- 61555,46		1	≤	1
0	6025,59	83641,94		0	-24469,238	16472,00		1	-43540,411	- 47 551,76		1	≤	1
0	362839,02	249660,12		1	-395970,27	66029,39		0	190159,02	75 767,04		1	≤	1
0	2573,19	74710,64		0	-15303,189	16472,00		1	-42095,611	- 32 863,34		1	≤	1
0	6439,88	73905,60		0	-14276,105	16472,00		1	-37199,323	- 38 379,38		1	≤	1
0	4202,72	72835,56		0	-12931,006	16472,00		1	-39106,478	- 37 515,63		1	≤	1
0	4640,03	72412,10		0	-12499,352	16472,00		1	-38352,374	- 36 281,81		1	≤	1
0	306942,20	222851,93		1	-349970,3	54534,39		0	148662,2	72 273,04		1	≤	1
0	14435,64	70385,83		0	-16304,951	16472,00		1	-25956,365	- 31041,54		1	≤	1
0	123574,05	101773,61		0	-176981,53	15639,69		1	72804,455	- 3 411,57		1	≤	1
0	3581,29	59988,41		0	2699,0981	15665,80		1	-32071,91	- 33 252,28		1	≤	1
0	135382,58	98145,21		0	-134310,67	27245,89		1	88088,978	11825,82		1	≤	1
0	5210,82	55967,13		0	6503,3513	14500,00		1	-27789,178	- 30 291,37		1	≤	1
0	3498,43	54669,25		0	10199,972	14262,20		1	-28960,368	- 21360,57		1	≤	1
0	7784,01	55473,16		0	4345,4131	14210,00		1	-24555,989	- 17 507,44		1	≤	1
0	36659,56	63778,02		0	-35249,187	14559,40		1	1868,356	- 22 200,49		1	≤	1
0	152785,80	98671,69		0	-129416,61	31351,90		1	106657,4	7 588,39		1	≤	1
0	160779,25	62916,97		0	-79221,31	35809,56		1	142211,39	26 707,96		1	≤	1
0	8640,21	53023,25		0	6813,4848	13508,20		1	-22102,594	- 19 230,25		1	≤	1
0	10697,84	52627,86		0	5749,3025	13276,20		1	-19516,963	- 25 633,50		1	≤	1
0	4557,17	51062,15		0	20594,7	13241,40		1	-25578,432	- 25 762,63		1	≤	1
0	10559,74	51478,71		0	6839,6341	12980,40		1	-18981,859	- 16 744,48		1	≤	1
0	10440,06	50903,25		0	7784,5881	12835,40		1	-18771,542	- 22 757,34		1	≤	1
0	72115,05	69609,19		0	-80812,888	13593,28		1	36152,646	- 7 303,14		1	≤	1
0	277522,82	169834,65		1	-232174,85	52901,39		0	167562,82	58 528,19		1	≤	1
0	10200,69	49730,44		0	9674,4961	12539,60		1	-18337,709	- 22 571,16		1	≤	1
0	60508,41	65219,85		0	-59195,934	13400,00		1	26644,006	- 8 155,69		1	≤	1
0	90517,16	73658,49		0	-80614,699	17853,52		1	54348,36	8 724,49		1	≤	1
0	220645,35	154945,00		1	-213468,63	39798,28		0	112365,35	50 567,41		1	≤	1
0	53427,53	62405,72		0	-51689,184	13095,60		1	20330,334	- 10 609,64		1	≤	1
0	227509,87	154905,79		1	-210596,14	41588,15		0	120949,87	45 418,59		1	≤	1
0	9767,99	47614,57		0	13090,868	12006,00		1	-17556,01	- 24 888,00		1	≤	1
0	9712,75	47360,77		0	13527,001	11942,20		1	-17466,048	- 23 502,60		1	≤	1
0	9565,45	46625,57		0	14690,021	11756,60		1	-17190,95	- 23 806,60		1	≤	1
0	177496,93	139327,54		0	-192578,16	30348,63		1	75016,926	33 586,62		1	≤	1
0	9431,96	45981,18		0	15744,008	11594,20		1	-16954,843	- 15 165,03		1	≤	1
0	9091,32	44324,82		0	18433,493	11176,60		1	-16345,08	- 21559,70		1	≤	1
0	6504,32	43392,06		0	22784,235	11089,60		1	-18734,078	- 21014,81		1	≤	1
0	6412,26	43020,15		0	23213,441	10996,80		1	-18614,942	- 12 963,04		1	≤	1
0	205341,03	102926,27		0	-121285,25	43605,36		1	161042,63	29 541,74		1	≤	1
0	8828,94	43037,13		0	20505,123	10851,80		1	-15868,262	- 16 895,86		1	≤	1
0	5514,63	41627,89		0	26133,055	10683,60		1	-18799,766	- 11542,91		1	≤	1
0	2840,17	40981,30		0	29983,614	10677,80		1	-21461,026	- 23 820,80		1	≤	1
0	54224,55	56383,99		0	-47193,446	10049,00		1	24970,945	- 8 568,99		1	≤	1
0	5850,67	41136,98		0	26456,73	10532,80		1	-18120,533	- 22 879,93		1	≤	1
0	8492,90	41403,74		0	23158,263	10440,00		1	-15267,096	- 18 854,50		1	≤	1
0	8469,89	41288,87		0	23339,985	10411,00		1	-15224,112	- 20 707,20		1	≤	1
0	153961,42	122370,19		0	-156849,85	26152,28		1	63481,422	30 388,68		1	≤	1
0	176516,28	123245,48		1	-150736,08	31919,29		0	90636,28	36 388,60		1	≤	1
			sum	6			sum	44						

Attachment 3

The biogas model with the initial solution for woodchips:

Biogas model

Objective Costs				**Objective Emissions**	
Sum costs Alt1	0	NOK/year	Sum GHG emissions Alt1	0	kg CO2-eq/year
Sum costs Alt2	-3273535,334	NOK/year	Sum GHG emissions Alt2	372992,507	kg CO2-eq/year
Sum costs Alt 3	-919005,96	NOK/year	Sum GHG emissions Alt3	-901604,18	kg CO2-eq/year
SUM Total Costs	-4192541,294	NOK/year	Sum Emissions	-528611,67	kg CO2-eq/year
Target Value	-4199421,443	NOK/year	Target Value	-1186663,6	kg CO2-eq/year

Objective function	Weight value	Weighed deviation		Max deviation
Deviation emissions	1	0,554539591	≤	0,554539591
Deviation costs	0,02	3,17019E-05	≤	0,554539591
MINIMIZE MAXIMUM DEVIATION		0,554539591		

Decision variables / **Choice constraint**

Alternative 1	cost	CO2-eq emitted	Alternative 2	Costs	CO2-eq emitted	Alternative 3	Costs	CO2-eq emitted	sum		
0	3721,12	127107,60	0	-79771,833	22217,71	1	-72891,684	- 72 544,20	1	≤	1
0	2859,19	108711,60	0	-58574,837	20153,84	1	-62665,608	- 62 736,02	1	≤	1
0	3408,64	82234,50	0	-24469,238	21779,00	1	-46157,364	- 48 959,19	1	≤	1
0	205255,65	164909,40	1	-442004,21	40579,80	0	32575,65	- 8 983,68	1	≤	1
0	1455,64	74109,60	0	-15303,189	19627,20	1	-43213,164	- 33 464,38	1	≤	1
0	3643,00	72401,40	0	-14276,105	19174,80	1	-39996,204	- 39 883,58	1	≤	1
0	2377,45	71853,90	0	-12931,006	19029,80	1	-40931,748	- 38 497,29	1	≤	1
0	2624,83	71328,30	0	-12499,352	18890,60	1	-40367,568	- 37 365,61	1	≤	1
0	173635,19	151157,40	1	-381332,85	37195,80	0	15355,185	578,51	1	≤	1
0	8166,14	67014,00	0	-16304,951	17748,00	1	-32225,856	- 34 413,37	1	≤	1
0	69905,03	72909,60	1	-172593,83	19021,20	0	19135,431	- 32 275,58	1	≤	1
0	2025,91	59151,90	0	2699,0981	15665,80	1	-33627,288	- 34 088,78	1	≤	1
0	76585,04	66523,00	1	-152275,77	17314,00	0	29291,435	- 19 796,39	1	≤	1
0	2947,73	54750,00	0	6503,3513	14500,00	1	-30052,272	- 31 508,50	1	≤	1
0	1979,04	53852,10	0	10199,972	14262,20	1	-30479,76	- 22 177,72	1	≤	1
0	4403,36	53655,00	0	4345,4131	14210,00	1	-27936,636	- 19 325,60	1	≤	1
0	20738,07	55215,20	1	-35249,187	14559,40	0	-14053,13	- 30 763,30	1	≤	1
0	86429,92	62984,50	1	-156577,8	16336,00	0	40301,522	- 28 098,80	1	≤	1
0	90951,77	25362,69	1	-132095,27	6578,51	0	72383,901	- 10 846,32	1	≤	1
0	4887,71	51005,10	0	6813,4848	13508,20	1	-25855,092	- 21 248,40	1	≤	1
0	6051,70	50129,10	0	5749,3025	13276,20	1	-24163,104	- 28 132,27	1	≤	1
0	2577,96	49997,70	0	20594,7	13241,40	1	-27557,64	- 26 827,08	1	≤	1
0	5973,58	49012,20	0	6839,6341	12980,40	1	-23568,024	- 19 210,99	1	≤	1
0	5905,87	48464,70	0	7784,5881	12835,40	1	-23305,728	- 25 195,89	1	≤	1
0	40795,01	52764,80	1	-80441,501	13798,60	0	4832,608	- 24 147,53	1	≤	1
0	156992,84	105011,80	1	-281123,18	25840,60	0	47032,835	- 6 294,66	1	≤	1
0	5770,46	47347,80	0	9674,4961	12539,60	1	-22767,936	- 24 953,80	1	≤	1
0	34229,21	51086,50	1	-59195,934	13400,00	0	364,808	- 22 289,04	1	≤	1
0	51204,96	52515,80	1	-88095,869	13717,60	0	15036,163	- 12 418,20	1	≤	1
0	124817,63	103407,40	1	-239429,81	25445,80	0	16537,625	- 970,19	1	≤	1
0	30223,61	49926,30	1	-51689,184	13095,60	0	-2873,595	- 23 089,07	1	≤	1
0	128700,84	101764,80	1	-240526,02	25041,60	0	22140,84	- 7 722,40	1	≤	1
0	5525,69	45333,00	0	13090,868	12006,00	1	-21798,312	- 27 169,58	1	≤	1
0	5494,44	45092,10	0	13527,001	11942,20	1	-21684,36	- 25 771,27	1	≤	1
0	5411,11	44391,30	0	14690,021	11756,60	1	-21345,288	- 26 040,87	1	≤	1
0	100408,85	97868,40	1	-203911,98	24082,80	0	-2071,155	- 7 872,51	1	≤	1
0	5335,60	43778,10	0	15744,008	11594,20	1	-21051,204	- 17 368,11	1	≤	1
0	5142,90	42201,30	0	18433,493	11176,60	1	-20293,5	- 23 683,22	1	≤	1
0	3679,45	41872,80	0	22784,235	11089,60	1	-21558,948	- 22 534,07	1	≤	1
0	3627,37	41522,40	0	23213,441	10996,80	1	-21399,828	- 14 460,79	1	≤	1
0	116160,07	54963,40	1	-174682,88	14084,80	0	71861,669	- 18 421,12	1	≤	1
0	4994,47	40974,90	0	20505,123	10851,80	1	-19702,728	- 18 958,09	1	≤	1
0	3119,59	40339,80	0	26133,055	10683,60	1	-21194,808	- 12 831,00	1	≤	1
0	1606,67	40317,90	0	29983,614	10677,80	1	-22694,532	- 24 484,20	1	≤	1
0	30674,47	43718,40	1	-44648,782	11455,80	0	1420,869	- 21 234,58	1	≤	1
0	3309,68	39770,40	0	26456,73	10532,80	1	-20661,516	- 24 246,51	1	≤	1
0	4804,38	39420,00	0	23158,263	10440,00	1	-18955,62	- 20 838,24	1	≤	1
0	4791,36	39310,50	0	23339,985	10411,00	1	-18902,64	- 22 685,57	1	≤	1
0	87094,97	86408,40	1	-165694,09	21262,80	0	-3385,035	- 5 573,12	1	≤	1
0	99854,10	82015,40	1	-171967,19	20181,80	0	13974,1	- 4 841,49	1	≤	1

Norges miljø- og biovitenskapelig universitet
Noregs miljø- og biovitskapelege universitet
Norwegian University of Life Sciences

Postboks 5003
NO-1432 Ås
Norway