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Optimising Anaerobic Digestion of Manure Resources at a Regional Level

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Abstract: An optimisation model was developed to give decision support on methods of managing manure resources within a region to reduce greenhouse gases and at the same time obtain economic profitability for the farmer. The model was tested by performing a case study on 50 farms in one region in Norway. Based on input data on the number of cattle and pigs on each farm, and the transport distance between each farm and the nearest centralised biogas plant, the model calculates the economic profit of the farmer and the greenhouse gas emissions for three manure management alternatives: (1) no biogas production; (2) farm scale biogas production; and (3) centralised biogas production. The model could minimise the greenhouse gas emissions, maximise the profit for the farmers or a combination of the two. Results from the case study showed that both options for anaerobic digestion (farm scale and centralised biogas production) are beneficial in terms of the reduction of greenhouse gases and can be profitable for the farmers. The case study has validated the functionality and usefulness of the model. Some improvements are suggested for further development and use.

Keywords: optimisation; anaerobic digestion; manure; greenhouse gas reduction

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1. Introduction

1.1. Anaerobic Digestion from Manure Resources

Agriculture accounts for about 10% of the total greenhouse gas emissions within the European Union [1]. Globally, emissions from manure management constitute about 7% of the emissions from agriculture [2]. Anaerobic digestion (biogas production) from manure can be identified as one of the most promising instruments in the reduction of methane emissions in agriculture, while at the same time contributing to the production of renewable energy [3].

Anaerobic digestion of manure resources can be carried out either in small scale biogas plants or in centralised plants. Biogas can be used to produce heat and/or electricity, or it can be upgraded to biomethane to be utilised as fuel in vehicles or fed into the natural gas grid [4]. Because of high investment costs, the upgrading of biogas to biomethane is carried out predominantly in large scale plants. Digestate, which is a co-product of biogas production, can be used as a fertiliser.

In many European countries, such as Germany, Slovenia, Denmark, the Netherlands, Austria and the Czech Republic [5], biogas is an important element in the production of renewable energy in the agricultural sector. In other countries such as Norway, Sweden and Finland, biogas production is chiefly based in the waste sector [6–8] and it has proven challenging to achieve the political objectives of increasing the amount of manure in biogas production. Farm scale biogas plants find it difficult to make an economic profit [9,10]. According to Jansson (2014), the challenges in achieving profitability in Swedish farm scale plants is due principally to low production per reactor volume, and difficulties in finding a profitable use for the gas produced [10].

In Norway, there are only a few farm scale plants, and their capacity is about 1% of the theoretical potential for manure [11]. This is a long way from the national target of the utilisation of 30% of manure from livestock for biogas production by 2020 [12].

There is a need for greater knowledge regarding the barriers to increased biogas production from manure, and for the development of models that provide decision support based on multiple criteria: reduction of the agricultural sector's impact on global warming and the achievement of economic profitability for the farmers.

1.2. Goal and Scope of the Study

This study has two principal objectives: (1) the development and testing of an optimisation model and a decision support tool that evaluates the environmental and economic impacts of various options for manure treatment at farms within one region; and (2) the advancement of knowledge with regard to ways of achieving the goal of increasing the amount of manure in biogas production. In addition, the application of the tool is intended to increase knowledge concerning the circumstances under which the manure should be transported to centralised plants, the point at which it is desirable for the farmers to invest in a farm scale plant, and which farms should not use their manure resources for biogas production.

1.3. Literature Review

No models with a similar approach and scope were found in the literature. A whole-farm optimisation tool was developed in the UK to assess the viability of farm based anaerobic digestion using a holistic approach, but it did not take into consideration centralised biogas production or greenhouse gas emissions [13]. Another model facilitated the economic and environmental assessment of the spatial distribution of livestock to reduce manure pressure in livestock intensive regions [14]. One optimisation model evaluated the size and location of biogas plants by applying an objective function that minimises the investment; minimises the operational, maintenance, and transport costs; and minimises social rejection [15]. Application of these models confirm the usefulness of developing optimisation models, but cannot be applied to answering the research questions posed in this study.

2. Materials and Methods

2.1. Optimisation Model

The decision support tool aims to solve a problem with two possibly contradictory objectives: that of choosing the most profitable solution for the farmers and that of minimising the emissions of greenhouse gases. A binary integer linear optimization model was developed. The model was inspired by an earlier model concerning the optimisation of waste handling [16] and based on the model developed by Bjerkestrand (2017) [17], with some improvements in data quality and functionality. The model was developed and run in Excel Solver [18].

2.2. Definition of Manure Treatment Alternatives

Three different alternatives were defined as possible manure treatment methods for each of the farms, as shown in Figure 1: (1) No biogas production: The farm is operated as usual without any changes in manure handling. Manure is used as fertiliser and spread directly on the fields without any treatment. (2) Farm-scale production of biogas and biofertiliser: The farm invests in a small-scale biogas plant that produces biogas from the manure on the farm. The biogas is used to generate heat to meet the heat demand on the farm. The digestate is then used as biofertiliser. (3) Centralised plant: The farmer signs a contract with a central biogas plant, which collects manure from the farm and returns the digestate as biofertiliser. The manure is co-digested with food waste from households and industry, and the biogas is upgraded to biomethane and used as a fuel in buses and other fleet vehicles. It is assumed that the farm is required to invest in new storage with cover for the pre-storage of manure, and that it uses the existing manure storage facilities for the biofertiliser.

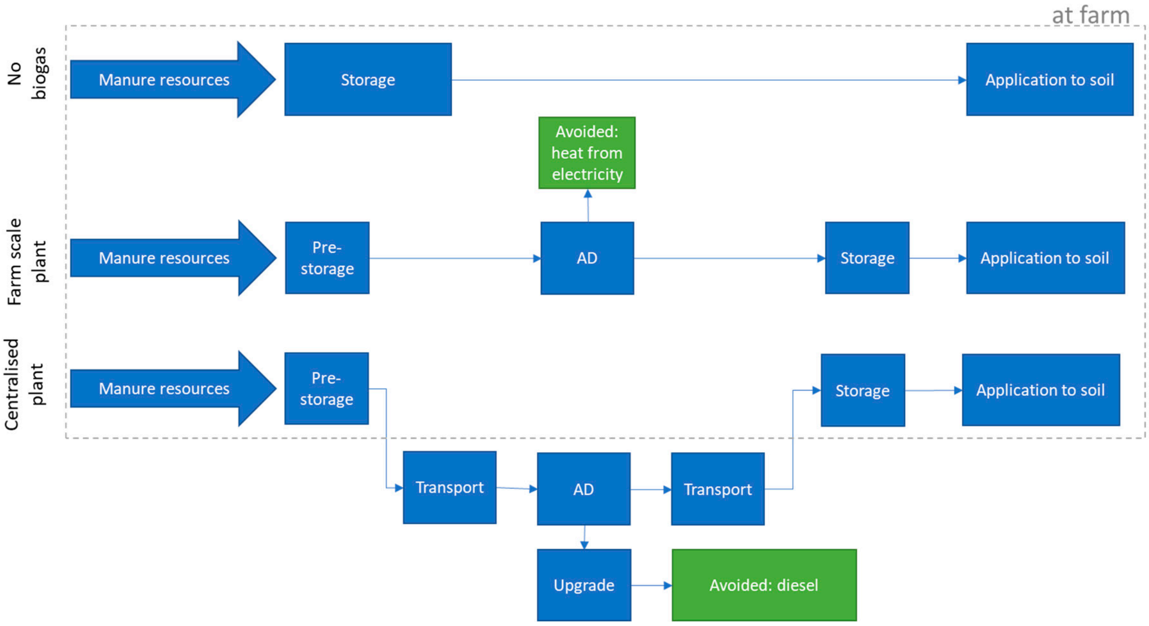

Figure 1. Flow chart for the three different manure management alternatives in the model.

The economic costs and income, the emissions and the avoided emissions of greenhouse gases for each of the alternatives are shown in Table 1 and are described in more detail in the following sections.

Table 1. Economic costs and income for the farmers and emissions and avoided emissions for each of the alternatives.

	No Biogas	Farm Scale Plant	Centralised Plant
Economic cost for farmer	No change	Investment in biogas plant, operational and maintenance costs	Investment in new storage, operational costs for delivering manure to plant and payment to centralised plant
Income for farmer	No change	Avoided cost for heat at farm and governmental support per tonne manure	Storage rent from biogas plant and governmental support per tonne manure
Emissions of greenhouse gases	Storage and spreading of manure	Pre-storage of manure, anaerobic digestion (energy use, capital goods), storage and spreading of digestate	Pre-storage of manure (emissions and capital goods), transport, anaerobic digestion (energy use and capital goods), transport, storage emissions and spreading of digestate
Avoided emissions of greenhouse gases		Production and distribution of heat from electricity	Production and use of diesel as fuel for transport

2.3. Input Data and Constraints

The calculation of the potential realistic biogas production for a farm scale plant at each farm was based on the theoretical biogas potential for the amounts of manure calculated by the number of cows and pigs on the farm; the realistic output of biogas from the digester, and conversion loss for heat generation, with data from Lyng et al. (2015) [19].

In the case of the centralised plant, all the produced biogas is assumed to be upgraded to biomethane and sold, while at the farm scale biogas plants some of the heat generated from the produced biogas is used to meet the heat demand of the anaerobic digester and the rest is used to cover the heat demand at the farm. The use of heat in a farm scale plant can vary significantly and is dependent on many factors, including the temperature of the manure entering the reactor, the surrounding temperature, digester technology and the hydraulic retention time. A study showed that a large proportion of the energy produced at two Norwegian farm scale plants was used to heat the input material (between 30% and 70% of the produced methane) [20]. The heat demand of small-scale biogas plants was estimated to be about twice as high as of large-scale plants per tonne input, while electricity use was about 50% [21]. In this study, it is assumed that the heat consumption on small scale plants is 53% of the produced biogas from cattle manure and 42% of the biogas produced from manure from pigs. The difference is due to a higher biogas yield for pig manure.

Finding an appropriate application for the energy produced proved to be challenging for some farm scale biogas plants. Between 2% and 75% of the energy produced at Swedish biogas plants was not used [10]. In the model presented in this paper, the avoided costs and the avoided emissions from heat use at the farm was constrained: The amount of substituted heat cannot be greater than the heat demand on the farm. The heat demand was calculated based on the number of animals. Energy demand for Norwegian cattle farms was estimated to be 1790 kWh/dairy cow/year based on data collected from one farm [22]. The number was verified by a review of figures in the literature. A literature review on the direct energy use on different types of farms found that annual energy use for cattle farms varied between 160 kWh/ dairy cow (New Zealand) and 2900 kWh/dairy cow (Switzerland) [23]. The heat demand on the Norwegian cattle farm seems to be in the upper area of the range found in the literature, which seems reasonable, since heat consumption in anaerobic digestion plants is high in the Norwegian climate [20], and energy efficiency studies on other farms in Norway seem to be within the same range [24,25].

Heat demand for pig farms was assumed to be 85 kWh/pig, calculated from a study on energy efficiency on a Norwegian farm [24]. This value is within the variations found in the literature: between 250 kWh/pig/year of which 15 kWh is heating (Denmark) and 1557 kWh/pig/year in the United Kingdom, of which 155 kWh is heating [23].

The current energy carrier for heat at the farms is assumed to be electricity, which is the most common energy carrier for heat among households in Norway (about 73%) [26]. This assumption can easily be changed in the model by replacing the cost and emissions factors for electricity with the costs and emissions factors of the specific energy carrier.

The farm scale plants were assumed to comprise a high rate sludge bed anaerobic digestion reactor developed in Norway [27,28]. The reactor is able to treat manure from a minimum of 5 m^3 manure to a maximum of 10 m^3 per day [29]. The maximum capacity of the farm scale plant was therefore limited to a maximum of 2840 tons per year in the model. On the farms with a larger amount of manure, the additional amount is assumed to be stored and applied to soil as in the *no biogas* alternative.

2.4. Objective Functions

The optimisation model contains three objective functions: (1) maximising the revenue of the farmers; (2) minimising the emissions of greenhouse gases; and (3) overall optimisation by maximising profit when impact on global warming is considered to be a cost. Each of the objective functions are described below.

2.4.1. Objective Function for Minimisation of Emissions

The objective function for minimising the greenhouse gas emissions minimises the total emissions for all the farms included in the model. Mathematically it can be described as follows:

$$\text{Minimise } \sum_{i=1}^{n} (X_{1,i} * GHG_{1,i} + X_{2,i} * GHG_{2,i} + X_{3,i} * GHG_{3,i}) \quad (1)$$

$$\text{Subject to } X_i \text{ } binary$$

$$X_{1,i} + X_{2,i} + X_{3,i} = 1 \tag{2}$$

where n is the number of farms in the model. $GHG_{1,i}$, $GHG_{2,i}$ and $GHG_{3,i}$ are the annual potential impacts on global warming for alternatives 1–3 for farm number i. $X_{1,i}$, $X_{2,i}$ and $X_{3,i}$ are variables that the optimisation model is permitted to change. $X_{1,i}$, $X_{2,i}$ and $X_{3,i}$ are defined as binary (can only be 1 or 0 because each farm cannot partly choose an option), and each farm can only choose one alternative.

2.4.2. Objective Function for Maximisation of Profit

The objective function for maximising the economic profit maximises the total profit for all the farms included in the model. Mathematically it can be described as follows:

$$\text{Maximise } \sum_{i=1}^{n} (Y_{1,i} * Profit_{1,i} + Y_{2,i} * Profit_{2,i} + Y_{3,i} * Profit_{3,i}) \tag{3}$$

$$\text{Subject to } Y_i \text{ } binary$$

$$Y_{1,i} + Y_{2,i} + Y_{3,i} = 1 \tag{4}$$

where n is the number of farms in the model. $Profit_{1,i}$, $Profit_{2,i}$ and $Profit_{3,i}$ are the potential annual profit for each of the three alternatives defined in the model for farm number i. $Y_{1,i}$, $Y_{2,i}$ and $Y_{3,i}$ are variables that the optimisation model is permitted to change. $Y_{1,i}$, $Y_{2,i}$ and $Y_{3,i}$ are defined as binary (can only be 1 or 0), and each farm can only choose one alternative.

2.4.3. Objective Function for Minimisation of Emissions and Maximisation of Profit

To be able to evaluate the reduction of greenhouse gases and economic profitability within the same objective function (overall optimisation), the two objectives are expressed in the same unit in the model. The potential greenhouse gas emissions ($GHG_{1,i}$, $GHG_{2,i}$ and $GHG_{3,i}$) are thus converted into monetary values ($MEV_{1,i}$, $MEV_{2,i}$ and $MEV_{3,i}$). The conversion of environmental issues into monetary values is a debated topic [30]. For this reason, several values per tonne of CO_2-equivalents were assessed in the case study.

The overall objective function for maximising the economic profit and minimising the greenhouse gas emission maximises the total profit when the emissions of greenhouse gases are internalised in the costs. Mathematically, this can be described as follows:

$$\text{Maximise}$$

$$\sum_{i=1}^{n} (Z_{1,i} * (Profit_{1,i} - MEV_{1,i}) + Z_{2,i} * (Profit_{2,i} - MEV_{2,i}) + Z_{3,i} * (Profit_{3,i} - MEV_{3,i})) \tag{5}$$

$$\text{Subject to } Z \text{ } binary$$

$$Z_{1,i} + Z_{2,i} + Z_{3,i} = 1 \tag{6}$$

where n is the number of farms in the model. $MEV_{1,i}$, $MEV_{2,i}$ and $MEV_{3,i}$ are the annual monetised emission values for alternatives 1–3 for farm number i. $Profit_{1,i}$, $Profit_{2,i}$ and $Profit_{3,i}$ is the potential annual profit for each of the three alternatives defined in the model for farm number i. $Z_{1,i}$, $Z_{2,i}$ and $Z_{3,i}$ are variables that the optimisation model is permitted to change. $Z_{1,i}$, $Z_{2,i}$ and $Z_{3,i}$ are constrained as binary (can only be 1 or 0 because each farm cannot partly choose an option), and each farm can only choose one alternative).

2.5. Calculation of Potential Effect on Global Warming

The potential effect on global warming for each of the three alternatives ($GHG_{1,i}$, $GHG_{2,i}$ and $GHG_{3,i}$ in Equation (1)) was calculated as an input to the optimisation model. The BioValueChain model was applied [19,31] using SimaPro 8.4.0 [32]. The background database used was EcoInvent 3.3 *allocation cut off by classification* (recycled content), as implemented in SimaPro [33]. The impacts included are described below and shown in Table 1. The environmental impact category used was IPCC 2013, where the current factors for methane, biological methane and nitrous oxide in kg CO_2-equivalents/kg emissions were 30.5, 27.75 and 265 respectively [34].

The direct emissions of greenhouse gases from the manure and digestate were based on values from the BioValuechain model and are shown in Table 2 [31]. Several studies have found that storage covers can reduce direct emissions during storage [35–37]. The centralised plant is thus assumed to require storage cover over the digestate storage to minimise the impact on global warming, while the storage at the farm scale facility is assumed to be without any cover.

Table 2. Estimated direct emissions from biomass in kg/tonne dry manure.

Life Cycle Phase	Emission	Cattle	Pig
Storage untreated manure	CH_4	10.2	4.8
	N_2O	0.123	0.789
Spreading of manure	CH_4	0	0
	N_2O	0.547	0.385
Pre-storage biogas	CH_4	8.63×10^{-99}	1.57×10^{-145}
	N_2O	1.18×10^{-100}	2.56×10^{-147}
Storage digestate (no cover)	CH_4	3.38	1.59
	N_2O	0	0
Storage digestate (with cover)	CH_4	0	0
	N_2O	0	0
Spreading of digestate	CH_4	0	0
	N_2O	0.468	0.329

Impact from capital goods (the biogas plant building and new storage) was included. Greenhouse gas emissions were based on the estimation of materials in anaerobic digestion plants by Brogaard et al. (2015) and inventory data for the materials from the EcoInvent database [33,38]. The avoided emissions from the generation and use of electricity was estimated to be 0.179 kg CO_2-equivalents/kWh, based on a mix calculated from the annual production, import and export in the Nordic and Baltic area in 2016 [39].

2.6. Calculation of Economic Profit

The annual profit for the farms for each of the alternatives ($Profit_{1,i}$, $Profit_{2,i}$ and $Profit_{3,i}$ in Equation (3)) was defined as annual income minus capital expenditures (Capex) and operational expenditures (Opex). Capex was annualised with a 6% interest rate with a 20-year payment period. The economic costs were calculated in Norwegian Kroner (NOK). In this paper, however, all values are converted to Euros, with an exchange rate of 8.953 NOK/Euro which was the annual average of daily figure in 2015 [40]. The annual profit for the *no biogas* alternative was defined as zero, because there are no extra costs or income when compared with the conventional operation on the farm.

In Norway, there are currently two economic support systems: investment support and support per tonne manure going to biogas production. Farm scale biogas plants can apply for investment support of up to 50% [41]. The support per tonne manure scheme was introduced in 2015 and is applicable to farms with their own biogas plant and to farms that deliver manure to a centralised biogas plant. For a farm scale biogas plant where all the manure goes to biogas production, the support can be calculated on the basis of the number of animals on the farm with a fixed tariff for each animal type, while for farms that deliver manure to a centralised plant, the support is calculated on the basis of dry matter content in manure, using a formula described in the regulations pertaining to grants for manure to biogas production [42].

In the farm scale biogas production alternative, there are two sources of income: governmental support per tonne manure for biogas production, and avoided costs for heat consumption on the farm. Estimation of the avoided cost for heat is based on a price of 0.06 Euro/kWh (0.548 NOK) [22]. The investment of farm scale biogas is assumed to be 111,694 Euro/year (1 million NOK) [29]. Each of the farms is assumed to receive 40% investment support. The maintenance costs are estimated to be 3.351 Euro/year (30,000 NOK) [29]. It is assumed that there is no need to invest in extra storage, as the farm can use the current infrastructure.

In the centralised biogas production alternative, the sources of income are storage rent from the large-scale biogas plant and support per tonne manure. The agreement between the biogas plant and the farms is assumed to be as follows, based on information relating to the agreements on an existing farm: The farmer pays 75% of the manure support to the biogas plant, and receives a storage rent of 5.9 Euro/tonne digestate (53 NOK). The centralised biogas plant covers the transport costs and the investment costs of the plant. The Capex is investment in a new storage tank that can contain one month of manure production [43], between 38,032 and 49,336 Euro (340,498 and 441,974 NOK). The Opex is assumed to comprise administrative costs of 52 work hours per year for managing storage and manure pickup and the application for governmental support.

In the two biogas production alternatives, the digestate is assumed to be used as fertiliser in the same manner as the manure in the *no biogas* alternative. The amount of digestate and the fertilising effect is assumed to be approximately the same as for manure [44,45]. It was also assumed that there is no need to invest in new spreading equipment.

2.7. Study Objects

The optimisation model was tested by performing a case study on 50 farms in Vestfold County in the east of Norway. Agriculture in Norway is dominated by relatively small farms in scattered locations. Vestfold is the county with the largest proportion of cultivated land. The farms selected were farms with cattle or pigs producing at least 5 m^3 manure per day. The cattle farms include farms with suckling cows, dairy cows and other cattle (heifers and calves), while the pig farms include those with breeding pigs and pigs for slaughter.

Information about the amount of manure produced was calculated from the number of animals on each farm and was provided by the County Governor of Vestfold [46]. Transport distances to the central plant were established based on their location and the location of an existing large-scale biogas plant treating manure and food waste from household and industry.

The farms were given an identification number from 1 to 50 and classified into types of farm as shown in Table 3: pig, cattle or combined farms. The farms with larger amounts of manure than the average for all the farms included in this study within the same farm type were categorised as large. The remaining farms were categorised as small.

Table 3. Type and size of farms included in the study.

Type of Farm	Small	Large
Cattle farm	6	2
Pig farm	22	9
Combined farm	6	5
All farms	34	16

3. Results

3.1. Optimisation of Manure Resources

In Figure 2, the results for the two alternatives *farm scale plant* and *centralised plant* relative to the *no biogas* alternative are plotted for all the farms in the region (without using the objective function).

The *x*-axis is the yearly profit for the farmer and the *y*-axis is the annual global warming potential for the handling of the manure. The blue dots refer to *farm scale plant* and yellow to *centralised plant*.

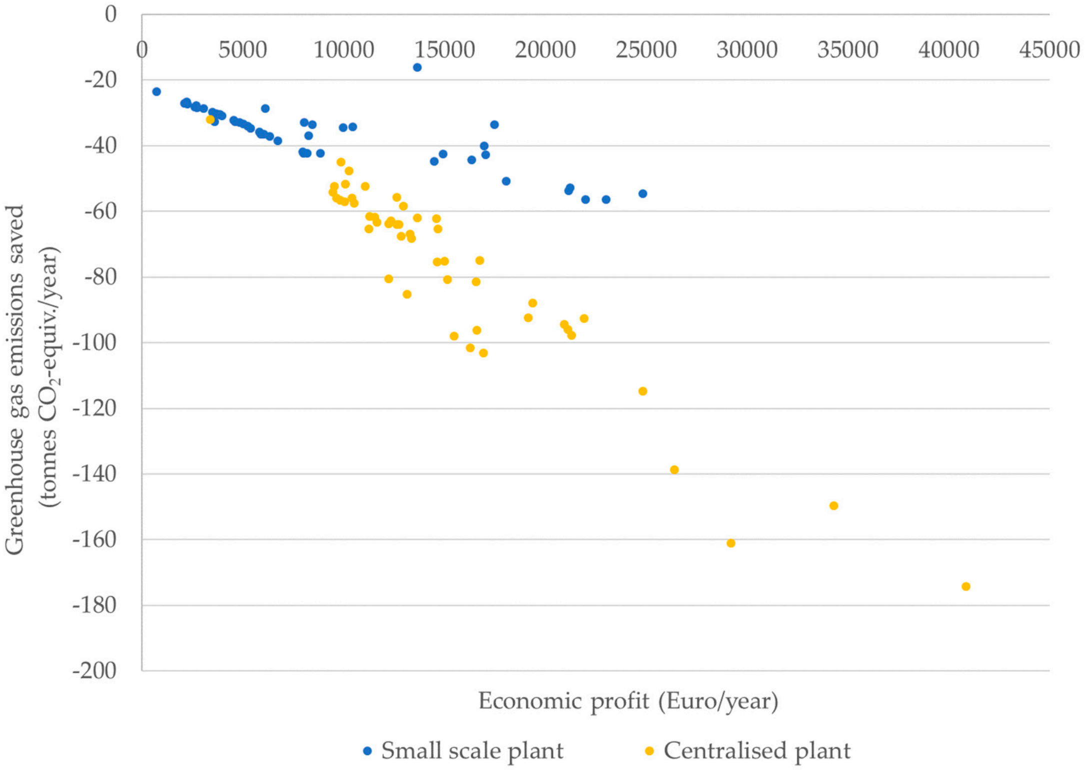

Figure 2. The economic profit and the saved greenhouse gas emissions for each farm relative to the *no biogas* alternative.

The environmental and economic results for the region when the objective functions were applied are shown in Figures 3 and 4. When the objective function for minimising GHG emissions (without considering economic cost and income) was used, the optimisation model chose the *centralised plant* alternative for all the farms included in the model. This is because the biogas from the centralised plant is upgraded and used as a fuel for transport. The benefits of the avoided emissions from the production and use of diesel compensates for the additional transport and the extra emissions from upgrading the gas to fuel quality. The benefits of the avoided emissions from heat generated from electricity are far fewer, which makes the farm scale biogas plant less preferred than the centralised biogas production.

When the objective function for maximising the economic profit of the farm was used, the optimisation model chose the *farm scale plant* alternative for 10 of the 50 farms in the model and the *centralised plant* alternative for 40 of the farms. The optimisation model did not choose the *no biogas* alternative for any of the farms, indicating that biogas production is profitable for all the farms in the region.

In the *farm scale plant* alternative, the governmental support for manure represented on average 70% of the income, and the avoided costs for heat represent about 30%. In the *centralised plant* alternative, the proportion of the governmental manure support that the farm kept (25%) was in average 27% of the income, while storage rent was 73%. The average annual economic result was 56% lower for the *farm scale plant* alternative than for the *centralised plant* alternative.

Of the 10 farms where the model chose the *farm scale plant* alternative, six were cattle farms categorised as small and four were combined farms (two categorised as small, and two as large). These farms received relatively high governmental support for manure in the *farm scale plant* alternative.

Due to current legislation, the model calculates the support per animal when manure is used for biogas production at the farm. When manure is supplied to a centralised plant, the support is calculated based on dry matter in the manure supplied, and it is assumed that the farmer pays 75% of the support to the biogas plant. The model chose the *centralised plant* alternative for all the pig and cattle farms that are categorised as large due to high income from storage rent.

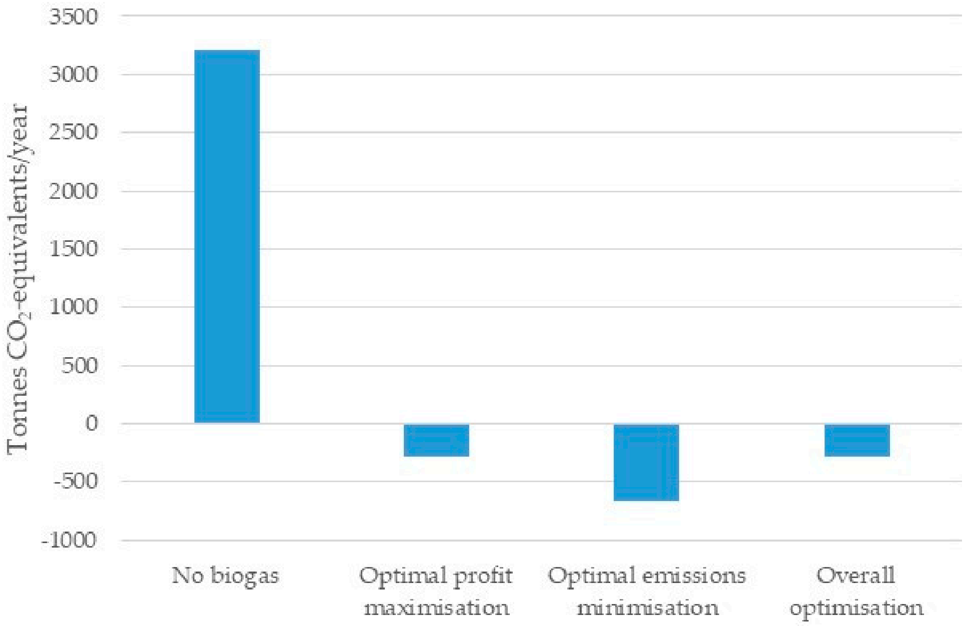

Figure 3. Potential effect on global warming per year for the region for the scenarios no biogas in the region, when applying optimisation of profit maximisation, emissions minimisation and overall optimisation.

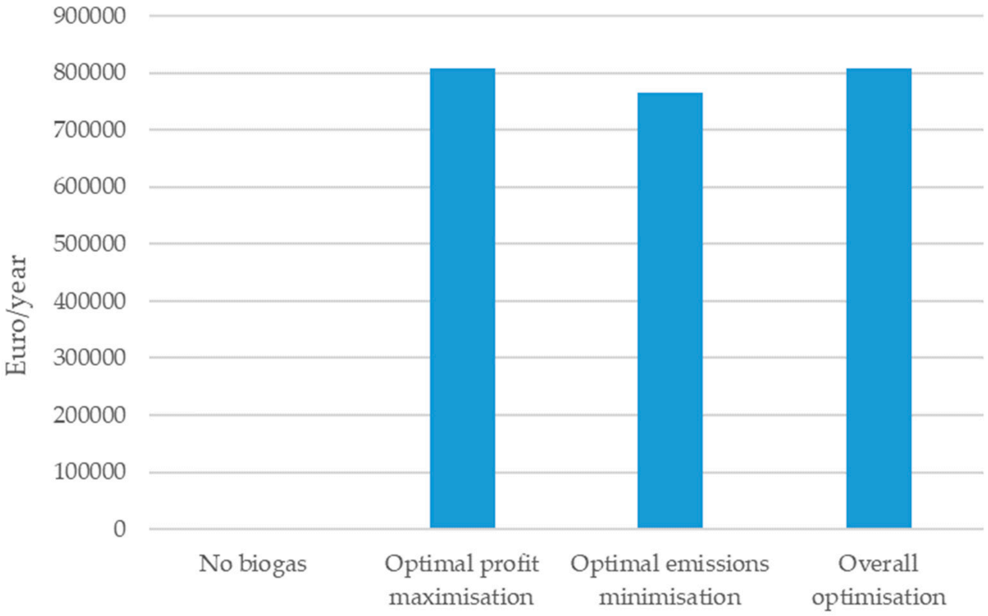

Figure 4. Annual profit for the region for the scenarios no biogas in the region, when applying optimisation of profit maximisation, emissions minimisation and overall optimisation.

When applying the overall optimisation objective function, taking into account both environmental impact and economic profit, the CO_2-emissions are regarded as a cost. Agriculture is not subject to the European emissions trading system. Use of the CO_2 quota price does, however, indicate the choice that farmers would be likely to make if they had the option of choosing between paying for the emissions or reducing them by using manure for biogas production. Use of the CO_2 quota price for 2016 when applying the overall optimisation function produces identical results to those found when the economic profit optimisation function is applied. This indicates that the CO_2 quota price would be too low to affect the farmers' decision. If the price increases, the share of farms supplying manure gradually decreases from 10 farm scale plants in the region at 7.8 Euro/tonne CO_2 (which was the quota price in 2016 [47]) to seven at 46.9 Euro/tonne CO_2 (which is a suggested CO_2-tax for non-quota sectors in Norway [48]) and three at 150 Euro/tonne CO_2, as shown in Figure 5.

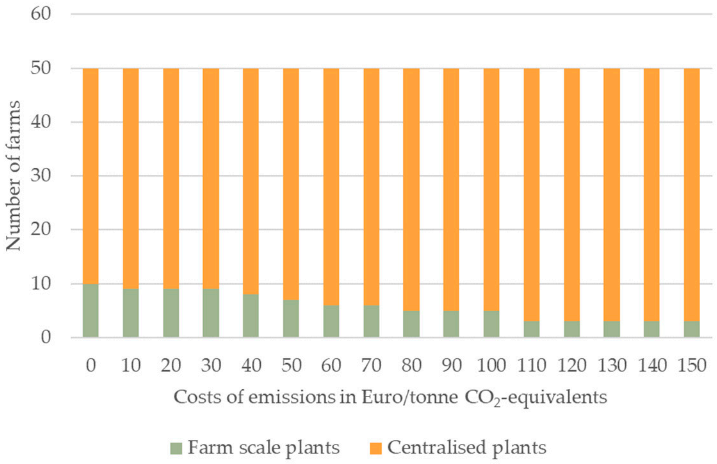

Figure 5. Results from overall optimisation for different cost factors per tonne CO_2-equivalents.

3.2. *Sensitivity Assessment*

The following aspects were tested in the sensitivity assessment: energy carriers and heat demand on the farm, the economic support system, agreements between the farmer and the centralised plant, the transport distance to the centralised plant and high costs for the farm scale alternative. Results from the sensitivity assessments are shown in Table 4.

Table 4. Results from sensitivity assessment.

	Minimisation of GHG Emissions			**Economic Profit Maximisation**		
	No Biogas	**Farm Scale Plant**	**Centralised Plant**	**No Biogas**	**Farm Scale Plant**	**Centralised Plant**
Base case	0	0	50	0	10	40
Energy demand at farm low	0	0	50	0	3	47
Energy demand at farm high	0	0	50	0	8	42
Substitution of oil combustion at farm	0	0	50	Not assessed	Not assessed	Not assessed
No investment support	0	0	50	0	3	47
No support for manure	0	0	50	0	0	50
No storage rent	0	0	50	0	47	3
Farm must pay for transport	0	0	50	0	17	33
High Capex farm scale plant	0	0	50	0	3	47
High Opex farm scale plant	0	0	50	0	5	45

3.2.1. Energy Carrier and Demand on the Farms

The literature showed a large variation in energy demand on the farms. In the sensitivity assessment, the values for heat demand per animal were set to a minimal and maximal value (see Section 2.3). When assuming a minimal heat demand on the farms, the optimisation model chooses the *farm scale plant* alternative for only five of the farms when optimising the economic profit. If the *centralised plant* alternative did not exist, the *no biogas* alternative would be the most profitable for nine of the farms. When assuming a maximal heat demand, there are no changes in the results when compared with the original results. The heat demand on the farm does not affect the results for minimising GHG emissions.

To be able to discuss the results from the model outside a Norwegian context, an assessment when assuming a fossil energy carrier on the farms was assumed. Substitution of heat from oil combustion reduced the emissions for the farm scale alternative, but not enough to change the results when applying the objective function of minimising the emissions. This can be explained by the large share of biogas used to heat the farm scale biogas reactor.

3.2.2. Economic Support System

In common with many other European countries, the Norwegian government has introduced economic incentive systems to increase biogas production. As described in Lyng et al. (2017), the economic incentives are predominantly aimed towards increasing biogas production, and not towards end use of biogas [8]. The importance of the incentive systems for the increase of manure to biogas production was evaluated by removing the support and applying the objective function for economic profit maximisation.

When removing investment support, the model suggested the *farm scale plant* alternative in the case of only five farms, which are small combined and cattle farms. This indicates that investment support is an important driver for increasing farm scale production of biogas. If the centralised biogas plant alternative was not available, the *no biogas* alternative would be more profitable than farm scale biogas production for 15 of the farms.

If the support per tonne manure was removed, the model suggested the *centralised plant* alternative for all farms. This is due to the income from storage rent. It is an unlikely scenario, as the centralised farm may not be willing to pay storage rent without receiving compensation for the manure treatment through the sharing of the manure support. If the *centralised plant* alternative did not exist, the use of manure for biogas production would not be profitable for any of the farms when the manure support was removed.

3.2.3. Agreements between Farmer and Centralised Plant

In the model, the agreement between the farmer and the centralised plant is that the farmer pays 75% of the governmental support for manure, and that the centralised plant pays for storage of digestate through a storage rent per tonne biofertiliser returned. The centralised plant covers the transport costs. These assumptions were based on an agreement between one such plant in Norway and surrounding farmers. Other agreement systems are possible. The significance of the type of agreement selected was tested by removing the storage rent income, and by shifting the transport cost from the centralised plant to the farmers.

When removing storage rent income, the model chose the farm scale biogas plant for all the farms. If the farm were to cover the transport costs, the model reduced the number of farms that supplied manure to the centralised plant from 40 to 3. This indicates that the agreement between the farmers and the centralised plant is of great importance when a farmer makes the decision on whether to supply manure to a centralised plant.

When the transport costs were assumed to be covered by the farmer, the centralised biogas production was chosen for three of the farms, while farm scale production was chosen for 47. The three farms comprised one small farm with a very short transport distance to the centralised plant, and two with a relatively small transport distance and large amounts of manure.

3.2.4. Transport Distance

The average transport distance from the farms to the centralised plant is 19 km, which is a short distance when compared with the distribution of farms in other regions in Norway. A sensitivity assessment was performed by increasing the transport distances and evaluating the effect on the result when using the objective functions for minimising greenhouse gas emissions and maximising the profit for the farms. The transport distance does not directly affect the economic profit for the farmer, as the centralised plant is assumed to cover the transport. In this sensitivity assessment, it was therefore assumed that the farmer covered the transport costs.

When increasing the average transport distance between the farms and the centralised plant, and applying the objective function of minimising emissions, the centralised biogas production alternative remained the most desirable option for all plants up to an average transport distance of 40 km (see Figure 6). With an average distance of more than 40 km, the amount of farm scale biogas plants steadily increased. For those farms situated furthest from the centralised biogas plant, the farm scale biogas plant option led to the largest reduction in greenhouse gases. The transport distances for those plants were, however, more than 100 km. This shows that in a global warming perspective, manure can be transported long distances if the centralised plant is contributing to substituting diesel in the transport sector.

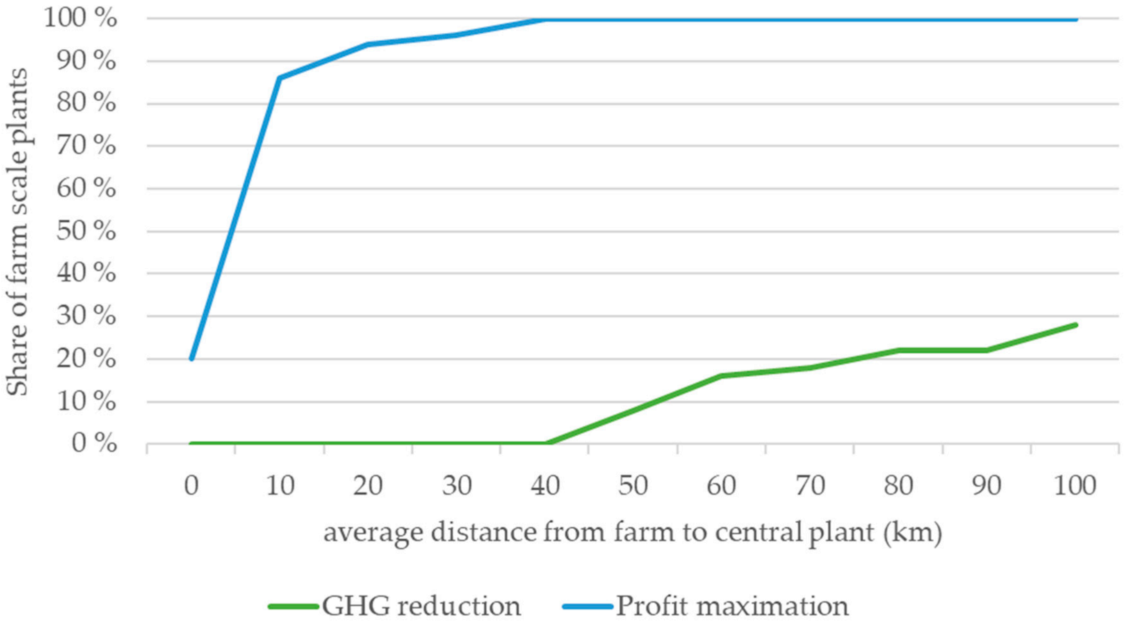

Figure 6. Sensitivity assessment of transport distance.

Assuming that the farmers have to cover the transport costs, the *farm scale plant* alternative became more profitable than supplying manure to the centralised plant for all the farms with an average distance of 40 km or more from the plant (the shortest distance is 15 km and the largest distance is 96 km). This implies that the transport costs are significant. Even if the farmers do not have to pay for transport, the transport cost is likely to affect the profitability for the farmers. The centralised plant would probably reduce the storage rent payment accordingly.

3.2.5. High Costs for the Farm Scale Alternative

The cost data used for farm scale biogas production in this paper are for a specific technology. Other technologies will have different investment and operational costs, however, finding transparent cost data for farm scale biogas technologies is challenging. The importance of the costs for farm scale production was tested by assuming that the Capex and the Opex was twice as high and applying the objective function for profit maximisation. When the investment costs of farm scale biogas production were increased by 100%, the model suggested the *farm scale* alternative for three farms. If the large-scale plant did not exist, the model suggested the *no biogas* alternative for 23 of the farms in the region. When the operational costs of farm scale biogas production were increased by 100%, the model suggested the farm scale alternative for five of the farms in the region. If the centralized plant did not exist, the no biogas alternative would be the most profitable for nine of the farms.

4. Discussion

4.1. Biogas Production from Manure as a Measure to Reduce Greenhouse Gases

The results from using the objective function for minimising greenhouse gas emissions showed that the two options for anaerobic digestion of manure (farm scale or centralised plant) are preferred when compared with storage and use of untreated manure as fertiliser. Transporting the manure to a centralised plant that upgrades biogas to biomethane represents a greater reduction of GHGs than farm scale biogas production. This is due to the avoided emissions from the production and use of diesel, as the biomethane is used as a fuel for transport. The farms were assumed to use electricity as the energy carrier for heat, which causes few avoided emissions in comparison with diesel when assuming a Nordic/Baltic electricity mix. Previous studies confirm the importance of energy carriers substituted by biogas and that biogas used to substitute diesel represent considerable emission reductions [4,19,49]. Even if the heat generated by biogas substituted heat from oil combustion on the farm, the centralised plant option appeared to be preferable due to internal use of heat from biogas in the small-scale plant. When the transport distance between the centralised plant and the farm was increased to over 100 km, however, the farm scale alternative was shown to be preferable to the centralised biogas production. A previous study investigating the energy performance in the life cycle of biogas production from manure found that the energy balance turned negative with transport distances exceeded approximately 200 km [21]. This confirms that the transport of manure is likely to be limited by economic costs before the emissions from transport compromise the positive effects of substituting fossil energy carriers.

There is currently only one large scale centralised biogas plant in Norway that uses manure from agriculture as input. In areas where no such centralised plant is available, farm scale production of biogas is a viable option in terms of reducing greenhouse gases, even if the gas is not used to phase out fossil alternatives. This is due to reduced emissions from storage and spreading. To achieve an even greater reduction, priority should be placed on finding ways of substituting fossil energy carriers on the farm or in the surrounding areas. This could be done through implementing technology development for cheaper small scale upgrading solutions or for use of raw biogas in tractors and other agricultural equipment currently using fossil fuels. A regional development plan for farm scale production, including a piping infrastructure and a centralised upgrading might also be a possible option.

4.2. The Profitability of Biogas Production for the Farmers

Optimisation of economic profit for the farmers showed that both farm scale and centralised biogas plants are profitable with the current support system. The only current centralised biogas plant in Norway treating manure from agriculture is located in the region assessed in this paper. The plant has agreements with 32 of the farms in the surrounding area. According to the model presented in this paper, supplying manure to the centralised plant is the most profitable option for 40 of the surrounding farms. This implies that the centralised plant could quite easily increase the number of agreements with surrounding farms on the delivery of manure to the plant, if desired.

The sensitivity assessment revealed that transport costs are likely to present a barrier in many regions in Norway. The region assessed in this paper has relatively short distances compared with other regions. A study on the economic impact of different configurations of biogas value chains in Norway revealed that inclusion of agriculture as a supplier of manure and receiver of digestate represented the least profitable option for the centralised plant [50]. Long transport distances will reduce the centralised plants' motivation to receive manure as a substrate from surrounding farms even more, and make the farm-scale alternatives more relevant.

The results for economic profit optimisation showed that farm scale biogas production is more profitable than no biogas production, for all the farms in the case study with the current support systems. This was also pointed out by Siegmeier et al. (2015) who claimed that biogas bears a potential to increase both environmental and economic output at the farm [51]. In reality, there are currently only six farm scale plants in Norway [11], and only one of the plants is located within the region assessed in this study. There are several possible reasons as to why farmers have not chosen to invest in farm scale biogas plant, although it appears to be a profitable option. The sensitivity assessment showed that most of the farms are dependent on the governmental support per tonne manure for the farm scale plant to be profitable. This support was introduced recently, and the impact of this support may not yet be visible. Investment support has been available for a longer period, but assessments showed that the investment support was not sufficient for most of the farms.

Insecurities about the duration of the current support system may cause hesitation among farmers to enter into a long-term commitment. Predictability is likely to be an important factor in whether they are willing to make the decision to be a supplier of manure or to invest in a small-scale plant. The long term perspective has also been identified as the most important success factor for agricultural biogas production in Sweden [52]. Investing in a plant may appear to be a high-risk project for the farmers, as there may be unforeseen investment and operational costs relating to the start-up of the plant. In addition, costs relating to acquiring the knowledge to run a small-scale biogas plant and the cost of the time spent by the farmer in running the plant were not included in the total costs. In the centralised biogas alternative, the plant takes all the risk.

Although the capital expenditure and the maintenance costs of the small-scale biogas plants was estimated based on the best available data for the technology, there are some limitations to the cost data used. The sensitivity assessment demonstrated the importance of low investment costs and the need for more knowledge about the actual costs of farm scale biogas production in a Norwegian context.

Norwegian farmers may not be motivated to invest in something that seems to be far from their conventional operation. The low energy prices in Norway mean that, unlike farms in some other European countries, they do not have the incentive to reduce their costs in relation to electricity and heating. A large proportion of farmers in Norway only work part time on the farm. This may present a barrier to expanding the business on the farm to include biogas production. In Sweden management of the farm scale biogas plants (knowledge, motivation and commitment) was identified as being an important factor for achieving profitability [10]. Investment in a farm scale plant requires a motivated farmer, who is willing to take a risk and is interested in learning about anaerobic digestion.

The results from this study indicate that economy is currently not the primary impediment to increasing the amount of manure for biogas production in Norway. Several factors can contribute to achieving the national goal of increasing the amount of manure to biogas production. These include initiatives to motivate large scale plants to use manure as a substrate, increasing knowledge with regard to the possibilities within funding for farm scale plants and measures to reduce the risks of unforeseen costs such as technology development and exchange of knowledge.

4.3. Further Improvement of the Optimisation Model

The testing of the optimisation model has verified that the model can give valuable input relating to the way in which manure resources in a region can be managed, in order to reduce the greenhouse gases from the agricultural sector, while obtaining profitability for the farmers. There are, however, some improvements that can be made in the future to expand the utility of the model and to obtain even more realistic results.

Utilising the model to perform a case study on a specific region in Norway has given insight into the functionality of the model and has enabled verification of the results from the economic profit maximisation against the actual number of biogas plants in the region.

The case study included only one type of farm scale technology, with its constraints, investment and operational costs. The greenhouse gas emissions were not modelled specifically for this type of reactor. Collection of more economic and environmental data and inclusion of other types of farm scale technologies should be considered in an improved version of the model.

As the literature showed significant variation in the energy demand at farms, the assessment could have been improved by collecting data on the actual energy demand and current energy carrier(s) on each farm (instead of calculating it and assuming electricity). Although the energy demand and energy carrier were shown to have little effect on the sensitivity assessment, this would have given more accurate results for the specific region being studied.

The model is applicable for regions in other countries provided that the cost data are adjusted to the local cost level and existing support systems and the energy carrier(s) substituted by biogas are changed.

5. Conclusions

An optimisation model was developed and used to assess the environmental and economic consequences of three different options for manure handling for 50 farms within one region in Norway. The model has been proven useful as a decision support tool and to provide insights in drivers and barriers relating to increased biogas production from manure resources in order to reduce greenhouse gas emissions.

The assessments showed that the most preferred option in terms of reduction of greenhouse gases was the centralised biogas alternative for all the farms, because of the use of upgraded biogas as a transport fuel to substitute diesel. The centralised biogas alternative also represented the most profitable option for most of the farms, but this was highly dependent on the agreement between the biogas plant and the farmer, which is likely to be affected by the transport distance.

Given the few existing plants in Norway, the results indicate that the barriers to increased biogas production from manure are not primarily economic. Incentives that motivate large scale plants to use manure as a substrate is likely to contribute to reducing the emissions of greenhouse gases in the agricultural sector in Norway. In regions where large-scale biogas production is not an option, efforts should be made to increase knowledge, provide predictability and to reduce the risks of unforeseen costs in farm scale biogas production.

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Nomenclature

AD	Anaerobic digestion
Anaerobic digestion	The production process of biogas and digestate
Biogas	Gas with about 60% methane content produced from organic matter
Biofertiliser	Digestate which is used as fertiliser
Biomethane	Refined biogas with a methane content of 96% or more, with same properties as natural gas
Capex	Capital expenditures
Digestate	The slurry which is a co-product from anaerobic digestion
GHG	Greenhouse gas
Opex	Operational expenditures

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