Economic, Social and Environmental Sustainability Assessment of Manure Processing in the Netherlands

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This research was conducted under the auspices of the Graduate School of Wageningen School of Social Sciences (WASS)

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Thesis
Submitted in fulfilment of the requirements for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus
Prof. dr. M.J. Kropff,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Wednesday 25 April 2012
at 1:30 p.m. in the Aula.

Solomie A. Gebrezgahber

Economic, social and environmental sustainability assessment of manure processing in the Netherlands

Thesis Wageningen University, Wageningen, NL (2012)

With references, with summaries in Dutch and English

ISBN 978-94-6173-210-1

Abstract

The intensification of livestock operations in the Netherlands has resulted in an increased concern on the environmental impacts of livestock operations. Poor manure management is often the basis of the environmental impacts. The general objective of this thesis is to assess the economic, social and environmental sustainability of manure processing and to develop a decision-support tool to assist decision makers in designing sustainable manure management systems. This thesis first explains dairy farmers' likelihood of adoption of manure separation technology from the farmers' attitudes and demographic and socio-economic characteristics. Next, the economic sustainability of anaerobic digestion of manure under different policy scenarios is analysed using a linear programming (LP) model. The economic analysis is extended to incorporate uncertainties associated with technical and economic parameters of manure digestion. Finally, the trade-offs between economic, social and environmental sustainability of manure processing taking several decision makers' views into account are analysed using multi-criteria decision making (MCDM) methods. Gross margin, greenhouse gases (GHG) emissions, ammonia (NH_3) emissions and land use change are used as criteria to measure the different aspects of sustainability. Findings show that farmers' attitudes towards the different attributes of manure separation significantly affect the likelihood of adoption. Results from the economic analyses indicate that despite current levels of subsidies provided to green gas production from anaerobic digestion of manure, there is a high probability of a negative net present value (NPV) when accounting for uncertainties in technical and economic parameters. Results from the MCDM study show that there is a conflict between the different sustainability criteria indicating that optimizing all criteria simultaneously is difficult. The highest GHG emissions savings from manure processing require high land use change and minimum land use change causes relatively low GHG emissions savings. A compromise between conflicting objectives is obtained indicating that the proposed method is a useful tool to assist policy makers in designing policies that enhance economically, socially and environmentally sustainable manure management systems.

Key words

Manure separation, anaerobic digestion, technology adoption, Monte Carlo simulation, economic social and environmental sustainability, multi-criteria decision making (MCDM), linear programming

Acknowledgments

The completion of this PhD thesis has been made possible due to the contribution and support of many individuals. I will try to express my sincere gratitude in the next few lines.

First and foremost, I would like to extend my sincere thanks to my co-promoter and supervisor, Dr. ir. Miranda Meuwissen with whom I worked very closely and whose guidance has been paramount to the successful completion of this thesis. Miranda, I have learnt a great deal from your guidance. Thank you for all the support and for thinking with me throughout the process of writing this thesis. It has been a pleasure working with you. We know each other for quite some time now and you not only were my thesis supervisor but also a good friend.

My deepest gratitude goes to my promoter Prof. dr. ir. Alfons Oude Lansink. Alfons, I value your guidance and I thank you for encouraging me to think and write critically. You know, it makes my day when you give me a positive reaction to my work and my writing. I have learnt a lot from you and I am grateful to you for that.

I would like to thank Gideon Kruseman for agreeing to work with me and for teaching me all the tricks about GAMS. I am grateful to Dora Lakner for providing me the survey data used in this thesis. I sincerely thank Prof. Carlos Romero for giving me the opportunity to visit his department at Technical university of Madrid and for teaching me all about multi-criteria decision making. I would like to thank Bram Prins, Jaap Petraeus, Rolando Montessori, Sjoerd Bokma, Stefan Schuurmans-Stekhoven and Wim de Hoop for all the interesting discussions and interviews we had.

To all my colleagues at the Business Economics group, thank you for making the work environment very pleasant. Especially my office-mate, Daphne Verreth, thank you for all the chat and the laughter we had. I couldn't ask for a better office-mate. To Anne Houwers, thank you for all the administrative support. Anne, I am grateful to you for agreeing to handle the administration of my thesis distribution in my absence, I really appreciate that.

On a more personal note I would like to thank my family for all their support and love. I am especially grateful to Garu Gebreyesus for his support and love.

Content

Chapter 1

General Introduction

1.1 Introduction

The Dutch livestock industry has witnessed an unprecedented growth since 1950. The favourable EU Common Agricultural Policy that provided price support for milk, exemption from import levy for imported feed coupled with price support for cereals have contributed to this development (Henkens and Van Keulen, 2001; Oenema et al., 2004). In addition to that, the port of Rotterdam enabled farmers to import large amounts of animal feed and fertilizers (Dietz and Hoogervorst, 1991). The high productivity and intensification of the livestock industry contributed substantially to the Dutch economy in terms of export of products and creation of employment.

The rapid growth of the livestock industry was accompanied by an increase in the volume of animal manure (Dietz and Hoogervorst, 1991). Manure from livestock production, when recycled to agricultural land, supplies plant nutrients and organic matter that can help to meet crop requirements and to maintain soil fertility. However, the large amounts of animal manure posed negative impacts on the environment. These environmental impacts were caused by emissions of nutrients such as nitrogen, phosphate and heavy metals to soils and surface waters, emissions of ammonia and greenhouse gases (GHG) including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) into the atmosphere. These emissions impacted environmental assets, i.e. the soil (accumulation of nutrients), the water (eutrophication) and the air, and lead to potential adverse effects on biodiversity and human health (Jongbloed and Lenis, 1998; Van den Brandt and Smit, 1998; Oenema, 2004).

Starting from around 1980, there has been growing awareness of and concerns about the environmental impacts of these intensive farming systems. As a consequence, the development of livestock production has been placed under strict environmental regulations (Henkens and Van Keulen, 2001). The manure policy in the Netherlands has become increasingly complex over the last decade, in an attempt to regulate the production and disposal of manure. A series of polices were introduced. First, a ban on the further expansion of intensive livestock farms was introduced. This was subsequently replaced by introducing mineral application standards per hectare followed by the launching of a nitrogen and phosphorus accounting system (MINAS) at farm level (Oenema, 1998). In addition to the national policy measures, agriculture in general, and livestock production systems in particular, are further regulated by EU policies which include the water framework directive and the air quality directive. The water framework directive encompasses a large number of other directives, of which the most important for livestock farming is the Nitrate Directive that aims to prevent and reduce water pollution caused by nitrates from agricultural sources. The air quality directive sets limits on the emissions of ammonia and nitrogen oxides into the atmosphere, so as to abate acidification and eutrophication (Oenema, 2004).

Environmental regulations coupled with growing public concerns about the environmental impacts of livestock operations forced farmers to change their ways of manure disposal. Farmers introduced other manure management practices that reduce the environmental impacts. Alternative mitigation strategies used by farmers are manure processing technologies. A wide range of processing technologies, which are either based on physical or biological processes, has been developed (Burton and Turner, 2003). The most common technologies already in use are separation and composting, and anaerobic digestion. A simple manure separation results in two fractions, a thin fraction and a solid fraction. One of the major attractive features of manure separation is its ability to concentrate manure solids, thus reducing the volume and expense of transportation. Anaerobic digestion of manure results in production of biogas and as a result the CH_4 emissions during storage of manure can be reduced and the energy from manure can be used as a substitute for fossil fuel.

The role of the livestock industry in the production of renewable energy and manure products through manure processing technologies has received considerable attention in the Netherlands. The high energy prices of the 1970s and early 1980s coupled with growing concerns about climate change caused by GHG emissions boosted research into the possibilities of livestock manure as a source of renewable energy and as a source of manure products that can replace artificial fertilizers (Negro et al., 2006). Despite an increased amount of work in research and development of manure processing, the adoption of such technologies is not successful in the Netherlands. Manure processing technologies are not without problems. Although the main objective of manure processing is to reduce the environmental impact, not all technologies achieve a reduction in pollution (Petersen et al., 2007) and most of the technologies are considered to be too expensive for the livestock farmer to adopt (Burton, 2007).

While there is a growing interest in manure processing, little is known about why farmers are not adopting the technology in the Netherlands. There is a need to develop approaches to investigate the decision-making behaviour of farmers who are potential adopters of manure processing technologies. Moreover, most of the work on manure processing focuses on the various economic and environmental aspects separately and hence provides partial insights. Instead, there is a need for an integrated approach to assess the economic, social and environmental sustainability of manure processing. Despite the growing interest in sustainability assessment of manure processing, assessing economic, social and environmental sustainability while taking decision makers' conflicting views of the different criteria into account is still an important problem that has not been addressed. A thorough assessment of sustainability of manure processing on the basis of a multi-dimensional criteria framework is essential for addressing the conflicting objectives of different decision makers and for promoting a robust decision-making process in the context of sustainable development.

1.2 Objective of the thesis

The general objective of this thesis is to assess the economic, social and environmental sustainability of manure processing and to develop a decision-making tool to assist decision makers in designing sustainable manure management systems. Manure processing technologies considered in this research are anaerobic digestion and manure separation. The specific objectives of this thesis are to:

- Identify factors influencing a farmer's likelihood of adoption of manure separation technology.
- Analyse the economic performance of anaerobic digestion of manure at farm level under different policy scenarios.
- Analyse the impact of uncertainties in technical and economic parameters on the economic performance of anaerobic digestion of manure at farm level.
- Analyse trade-offs between economic, social and environmental sustainability of various manure processing systems at regional level in an integrated assessment.

1.3 Outline of the thesis

This thesis consists of six chapters which are as follows. Chapter 2 analyses the likelihood of adoption of manure separation technology to mitigate environmental hazards emanating from livestock production. This chapter investigates factors that determine the likelihood of a dairy farmer having a strategy to adopt manure separation technology. This is analysed by including attitude variables in addition to demographic and socio-economic characteristics in an explanatory model of behaviour. Moreover, the empirical model is used to analyse the impact of demographic and socio-economic characteristics on the attitudes of farmers towards the different attributes of the technology.

Chapter 3 analyses the economic performance of anaerobic digestion of manure and other co-substrates at farm level under two policy scenarios. The first policy scenario focuses on the current debates on the treatment of digestate, i.e. the end product from the process as a replacement for artificial fertilizer, while the second policy scenario focuses on government subsidy to renewable energy production. Scenario analysis is carried out using a linear programming (LP) model to determine the optimal application of digestate.

Chapter 4 extends the economic analysis and addresses the uncertainties associated with technical and economic parameters of anaerobic digestion of manure. This chapter explicitly accounts for risk by developing a stochastic simulation model in which variables such as investment costs, biogas yield, conversion efficiency and price of co-substrates vary within certain ranges.

Chapter 3 and Chapter 4 focus on the economic sustainability of manure digestion. Chapter 5 extends the economic analysis into an overall sustainability assessment of manure processing. In this chapter the economic, social and environmental sustainability of manure processing is assessed by applying multi-criteria decision making (MCDM) methods. Several MCDM methods are used to determine optimal regional manure management planning from different decision makers' point of view. This chapter examines key regional trade-offs arising between economic, social and environmental aspects of manure processing.

Finally, Chapter 6 discusses methodological and data issues of the thesis as well as the main findings and their policy and business implications. Suggestions for future research are also outlined in this chapter.

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Chapter 2

A Study on the Factors Influencing Adoption of Environmental Damage Abatement Technology: The Case of Livestock Manure Separation

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Submitted for publication

Abstract

There has been a growing concern in many countries on the environmental impacts of manure from livestock operations. A variety of strategies and technologies have been developed and applied as a means to mitigate these environmental hazards. Manure separation technologies are essential for sustainable livestock operations in areas with high livestock density as these technologies result in a better utilization of manure and a reduced environmental impact. Technologies for manure separation are well researched and are ready for use. However, the adoption of manure separation is not successful in the Netherlands. This chapter investigates the role of farmer's demographic and socio-economic characteristics and farmer's attitude towards technology-specific attributes in influencing the likelihood of a farmer having a strategy to adopt manure separation technology. The analysis used survey data collected from 350 Dutch dairy farmers in 2009. The results show that the age and education level of the farmer and farm size are important variables explaining the likelihood of adoption. Farmer's attitude towards the different attributes of manure separation technology significantly affect the likelihood of adoption. The study generates useful information for policy makers, technology developers and distributors in identifying the factors that impact decision-making behavior of farmers.

Key words

Manure separation, technology adoption, ordered probit, factor analysis, dairy farming

2.1 Introduction

The environmental concerns and impacts of livestock production systems have been the actual concerns of many countries, especially those countries and regions with dense animal populations. Environmental impacts include discharges to soils and surface waters of nitrogen, phosphate and heavy metals as well as emissions into the atmosphere (Jongbloed and Lenis, 1998; van den Brandt and Smit, 1998), impacting three environmental assets including the soil (accumulation of nutrients), the water (eutrophication) and the air (Jongbloed and Lenis, 1998; van den Brandt and Smit, 1998). This has prompted governments, livestock farmers and other stakeholders to explore alternative manure handling and utilization methods that result in a reduced environmental impact. Since 1985, the Dutch government has implemented several laws and regulations to reduce the environmental impact of livestock farming by preventing the growth of livestock production and by reducing manure production and use. Excessive use of animal manure has been regulated by application standards since 1987, followed by the launching of the Mineral Accounting System (MINAS) in 1998. The Manure Transfer Agreement System (MTAS) was subsequently introduced in 2002 (Berentsen and Tiessink, 2003).

In addition to governmental laws and regulations, different strategies and technologies have been developed and applied as a means to mitigate the environmental hazards from livestock operations. Adjusting feed intake is considered an effective way to reduce nutrient losses to the environment (Jongbloed and Lenis, 1998). Furthermore, different manure storage systems and manure application procedures have contributed to the reduction of ammonia emissions (Smith et al., 2009). Different processing technologies based on biological and physical processes have been developed and applied to reduce the emissions of greenhouse gases and ammonia and to produce energy. The technologies already in use include separation and composting, anaerobic digestion and aeration. While alternative management technologies are readily available, there exists a challenge for many countries in the adoption and diffusion of such technologies on a wider scale (Martinez et al., 2009). There are technologies that generate manure products such as the solid fractions of manure that are rich in phosphate, but the market for the end products is not established or is uncertain. This limitation renders investment in manure processing technologies uncertain, which impacts the economic feasibility of the technology and, hence, its adoption.

This chapter addresses a specific case study of the adoption of manure separation. Research has suggested that manure separation technologies are essential for livestock operations in areas with high livestock density because they result in better utilization of manure and reduced environmental impact (Moller et al., 2000; Melse and Verdoes, 2005; Burton, 2007; Melse and Timmerman, 2009). Manure separation reduces off-farm disposal costs of manure and produces manure products that can compete with artificial fertilizers. However, manure separation is associated with a number of uncertainties causing most farmers to apply conventional disposal methods and fertilizer management (Schroder et al., 2009). Despite an increased amount of work in research and development of separation technologies, the adoption of the technology is not successful in the Netherlands as only few farmers have taken the initiative to invest in manure separation technologies. In this study, we make an *ex-ante* analysis to identify factors that influence a dairy farmer's intention to adopt manure separation technology. Specifically, we seek to analyse the effect of a farmer's demographic and socio-economic characteristics and a farmer's attitude towards manure separation technology on a farmer's intention to adopt the technology. Moreover, this study analyses the effect of demographic and socio-economic characteristics on the attitude of a farmer towards the different attributes of manure separation technology. Of particular interest to policy makers and technology developers is the role that farmers' attitudes, along with other factors, play in the adoption process and, thereby, identify farms that are most likely to adopt separation technologies. Understanding the perceptions and attitudes of farmers is essential as attitudes are important in determining the adoption of a technology (Adesina and Zinnah, 1993; Adesina and Baidu-Forson, 1995).

The chapter is organized as follows. Section 2.2 presents an overview of manure separation in the Netherlands. Section 2.3 presents the conceptual framework and methodology, followed by section 2.4 outlining the dataset. Results are given in section 2.5 and section 2.6 concludes the study.

2.2 Description of manure processing technology

One of the major attractive features of manure separation is its ability to concentrate manure solids, thus reducing the volume and expense of transportation. The purpose of separation is to achieve a manure fraction with a limited volume, which is more saleable than raw manure and which can compete with chemical fertilizers. A simple manure separation results in two fractions: a liquid fraction with a low dry matter and a solid fraction. Phosphate, accumulated in the solid fraction, can be transported over long distances. The liquids can be applied on the farmer's own farm or near the manure source as a nitrogen fertilizer. This results in lower transportation costs and a reduced environmental impact. There are various separation techniques and the amounts of dry matter and nutrients included in the solid fraction are dependent on the technology used. A selection of different technologies is illustrated by Moller et al., (2000).

In the Netherlands, manure processing has been practiced as early as the 1970s, when a range of policy instruments were introduced in attempts to limit the environmental impacts of livestock production systems (Melse and Timmerman, 2009). The driving forces for manure processing initiatives, according to Melse and Timmerman (2009), are summarized as the introduction of stringent nutrient legislation on land application of minerals and the high farm disposal cost of untreated manure. The most commonly used separation techniques are based on simple technological solutions where solids are mechanically separated from liquids. Such techniques include screw pressing, centrifugation, filtration or sieving (Burton, 2007). The total cost of the separation process varies depending on the sophistication and efficiency of the technique utilized (Moller et al., 2000). Sedimentation, mechanical screen separation and centrifugation are simple techniques that are cost effective, while biological treatments, evaporation, ultrafiltration and reverse osmosis are complex and expensive techniques (Burton, 2007).

2.3 Conceptual framework and methodology

The adoption of a technology in agriculture is an important theme of agricultural research and has been studied extensively by economists and sociologists for several decades (Feder et al., 1985; Nowak 1987; Feder and Umali, 1993). Several studies have attempted to explain and predict key determinants of technology adoption and the diffusion process by developing core sets of theoretical frameworks. One of the widely recognized technology adoption models is the innovation-diffusion model, following the early works of Rogers (1983). The innovation-diffusion model suggests that the complexity and compatibility of the technology, the characteristics of the potential end users, the individual’s perception about the technology and the communication channels determine the adoption and diffusion of new technologies.

On the empirical side, there is an abundance of adoption literature that seeks to explain a farmer’s adoption decisions with respect to agriculture. It has generally been found that adoption is a function of farm and farmer characteristics and specific features of the particular technology (Rahm and Huffman, 1984; Marra and Carlson, 1987; Feder and

Umali, 1993). Studies have shown that a farmer's characteristics such as age, education and experience influence the adoption decision though with differing signs and levels of significance based on the type of technology studied, the locale and the statistical methods used (Knowler and Bradshaw, 2007). The age of a farmer has been regularly assessed in adoption studies and it is commonly hypothesized that the age of a farmer is negatively related to adoption (Adesina and Zinnah, 1993; Adesina and Baidu-Forson, 1995; Oude Lansink et al., 2003). It is assumed that older farmers have a short planning horizon and are less likely to adopt new technologies. In analyzing the strategic planning of Dutch pig farmers, Oude Lansink et al. (2003) included several explanatory variables and found that in addition to age, having a successor is important in determining the planning horizon of farmers. Education and experience of the farmer have been found to have a positive effect on adoption (Rahm and Huffman, 1984; see Knowler and Bradshaw, 2007 for an overview). In addition to characteristics of the farmer, farm characteristics such as the size of the farm are frequently included in adoption studies. As outlined by Feder and Umali (1993) and Knowler and Bradshaw (2007), farm size has been shown to positively affect adoption decisions, thus indicating that owners of larger operations are more willing to invest in new technologies. Characteristics of the technology are only minimally included in adoption studies (Adesina and Zinnah, 1993). A study by Batz et al. (1999) found that features of a technology such as relative complexity, relative risk and relative investment characteristics have significant influence on adoption. Additionally, other studies, though limited, indicated that attitudes of farmers significantly condition adoption decisions (Adesina and Zinnah, 1993; Adesina and Baidu-Forson, 1995; Negatu and Parikh, 1999; Adrian et al., 2005).

In this study, we assumed that farm and farmer characteristics, along with farmers' attitudes toward manure separation technology, contribute to each individual farmer's subjective utility of adopting manure separation technology. At this point, we faced dual problems. First, there exists a correlation between attitude variables from survey data (a description is given in the next section), and second, there exists an endogeneity problem as attitudes are partly determined by farm and farmer characteristics. To disentangle partly endogenous effects, we use a multi-step approach modeled after Kububo et al. (2010). This includes i) the orthogonalization of interrelated soft variables, ii) the extraction of the idiosyncratic elements of soft variables and iii) the estimation of the probability that a farmer has a strategy to adopt, which we were originally interested in. This is shown in Figure 2.1.

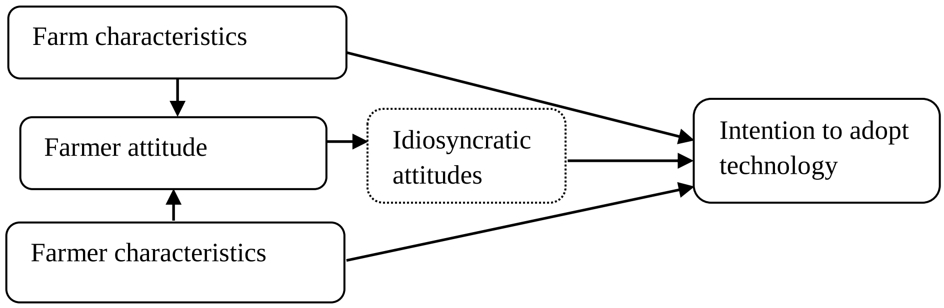

Figure 2.1 Conceptual framework of a farmer's intention to adopt a technology

A continuum of three steps are used to estimate the "willingness to adopt" probability.

Step 1: Factor analysis

As the data set pertaining to farmers' attitudes toward manure separation technology consists of a large number of interrelated variables, a factor analysis is used in the first stage. Factor analysis reduces the dimensionality of the data set and creates a limited number of meaningful orthogonal alternative variables while retaining, as much as possible, the variation present in the data set (Jollife, 2002).

The basic idea underlying the factor analysis is that p observed random variables, $X=[x_1, x_2, \ldots, x_p]$ can be expressed as linear functions of m ($< p$) latent factors, $F=[f_1, f_2, \ldots, f_m]$:

$$X_j = \sum_{k=1}^{m} \lambda_{jk} f_k + e_j \tag{2.1}$$

where λ_{jk}, $j= 1,2, \ldots, p$; $k= 1,2,\ldots,m$ denote factor loadings, and e_j, $j= 1,2,\ldots, p$ are error terms or specific factors. This equation can be rewritten in matrix notation as:

$$X = \Lambda F + e \tag{2.2}$$

where F is the m-dimensional vector of the m factors, and Λ is a (p x m) matrix of the loadings of the common factors. The factors obtained here are orthogonal linear combinations of the original variables and, therefore, have the property that each factor is uncorrelated with all others (Jollife, 2002). Through a rotation of the factor space, we obtain factors that have conceptual and empirical meaning.

Step 2: Seemingly unrelated regression estimation

The differences in the attitudes of farmers involved in the adoption of a technology are likely to be related to the farmer and farm characteristics (Burton et al., 2003). Because attitudes of farmers are not necessarily independent of the farm and farmer characteristics, the factors obtained in the first stage are regressed on the farm and farmer characteristics as a system of linear equations using seemingly unrelated regression estimation (SURE) in the second stage. SURE is used when a subset of right-hand side variables are the same (Zellner, 1962). The set of equations can be written as:

$$F_k = X_k \alpha_k + \varepsilon_k \qquad k = 1, 2, \ldots, m \tag{2.3}$$

where F_k is the (m x 1) vector of factors obtained in stage one, X_k represents a block of the diagonal matrix of explanatory variables (farm and farmer characteristics), α_k is the (*m x 1*) vector of the coefficient of explanatory variables and ε_k is the error term, which is normally distributed with $E(\varepsilon_k) = 0$. We can rewrite the equation in matrix form as:

$$\begin{bmatrix} f_1 \\ f_2 \\ \cdots \\ f_m \end{bmatrix} = \begin{bmatrix} x_1 & 0 & \ldots & 0 \\ 0 & x_2 & \ldots & 0 \\ \ldots & \ldots & \ldots & \ldots \\ 0 & 0 & \ldots & x_m \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \cdots \\ \alpha_m \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \cdots \\ \varepsilon_m \end{bmatrix} \tag{2.4}$$

We then use the residual terms, ε_k, of each of the equations, which represent the idiosyncratic element of the measured attitudes of farmers as explanatory variables in the willingness to adopt equation. The purpose of using the error terms from SURE as explanatory variables in the final stage is to overcome the endogeneity problem while taking into account the idiosyncratic attitudes of farmers.

Step 3: Ordered probit model

In the final stage, we estimate the probability that a farmer has a strategy to adopt manure separation technology. Because the dependent variable (strategy to adopt) takes more than two values and these values have logical ordering, an ordered probit model, which is estimated using the maximum likelihood method (Maddala, 1983, p46), was used to evaluate the factors that influenced the probability to adopt strategy. The dependent variable determines whether livestock farmers perceive manure separation as a strategy for manure management in the future.

The ordered probit model is based on a latent response variable, y_i^*, which can be defined as a function of observed variables, x_i, which represent farm and farmer specific characteristics, the error terms from SURE, ε_i, which represent the idiosyncratic element of measured attitudes, and unobserved variables, u_i, as follows:

$$y_i^* = \beta' x_i + \gamma' \varepsilon_i + u_i \tag{2.5}$$

The relationship between the observed variables y and the latent variable y_i^* is given by:

$$\begin{aligned} y_i &= 1 \quad \text{if } y_i^* \le \mu_1, \\ y_i &= 2 \quad \text{if } \mu_1 < y_i^* \le \mu_2, \\ y_i &= 3 \quad \text{if } y_i^* > \mu_2 \end{aligned} \tag{2.6}$$

where μ's are cut-off points representing discrete categories that the latent variable falls into and are to be estimated jointly with β' and γ' which are, respectively, a vector of coefficients for the farm and farmer characteristics and the idiosyncratic attitudes of farmers (error terms obtained in stage 2). In this formulation, the $\beta' x_i + \gamma' \varepsilon_i$ is an index function such that higher values for this index correspond with, on average, larger values for y_i. For example, a positive (negative) β and/or γ implies that the corresponding variable increases (reduces) a farmer's willingness to adopt manure separation technology. The u, a vector of error terms, is normally distributed N $[0,\sigma^2]$.

The implied probabilities that the ordered dependent variable y takes the different values can now be given by:

$$P(y_i = 1|x_i) = P(y_i^* \leq \mu_1|x_i) = \Phi(\mu_1 - \beta' x_i - \gamma' \varepsilon_i)$$
$$P(y_i = 2|x_i) = \Phi(\mu_2 - \beta' x_i - \gamma' \varepsilon_i) - \Phi(\mu_1 - \beta' x_i - \gamma' \varepsilon_i)$$
$$P(y_i = 3|x_i) = P(y_i^* > \mu_2|x_i) = 1 - \Phi(\mu_2 - \beta' x_i - \gamma' \varepsilon_i) \qquad (2.7)$$

where Φ is the cumulative probability function of a standard normal distribution.

Coefficient estimates are obtained by maximizing the value of the log-likelihood equation, which is the sum of the individual respondents' log probabilities and is given by:

$$L = \sum_{y_i=1} \log \Phi(\mu_1 - \beta' x_i - \gamma' \varepsilon_i) + \sum_{y_i=2} \log \Phi(\mu_2 - \beta' x_i - \gamma' \varepsilon_i)$$
$$- \Phi(\mu_1 - \beta' x_i - \gamma' \varepsilon_i) + \sum_{y=3} \log(1 - \Phi(\mu_2 - \beta' x_i - \gamma' \varepsilon_i)) \qquad (2.8)$$

The marginal effects of the explanatory variables on the probabilities are not equal to the coefficients. For the binary explanatory variables, the marginal effect is the difference in probabilities between setting the explanatory variable to 1 and to 0, setting the other explanatory variables at their sample means. The marginal effect of continuous variables is the change in the probabilities of the different outcomes with a change in one of the explanatory variables. The marginal probabilities are calculated by evaluating the density functions at the relevant points and multiplying by the associated coefficient from the ordered probit model as:

$$\frac{dprob(y_i)}{dx_i} = \left[\Phi(\mu_{i-1} - \beta' x_i - \gamma' \varepsilon_i) - \Phi(\mu_i - \beta' x_i - \gamma' \varepsilon_i)\right]\beta \qquad (2.9)$$

$$\frac{dprob(y_i)}{d\varepsilon_i} = \left[\Phi(\mu_{i-1} - \beta' x_i - \gamma' \varepsilon_i) - \Phi(\mu_i - \beta' x_i - \gamma' \varepsilon_i)\right]\gamma \qquad (2.10)$$

2.4 Data description

A survey based on a postal and computerized questionnaire, of representative dairy farms in the Netherlands was designed to elucidate livestock farmers' knowledge of and attitude towards manure separation technology as a livestock waste management option. The questionnaire consisted of three parts, namely, questions related to i) the farmer's knowledge of manure legislation and manure separation, ii) the farmer's perceptions of the different attributes of manure separation and iii) the farmer's perceptions of other solutions to manure problems. Respondents were asked to give a score to a statement based on a Likert scale from 1, indicating strongly disagree, to 7, indicating strongly agree. The sample for the survey consisted of those farms that are part of the Dutch Farm Accountancy Data Network (FADN). The study was based on cross-section data collected in the year 2009. A total of 350 farmers were contacted. Because of non-response and missing observations, 111 surveys were usable in the final analysis i.e. the effective response rate was 31%. In addition to the questionnaire, data from agricultural census were used. Data pertaining to farm and farmer characteristics were taken from agricultural census, while data pertaining to knowledge and attitude information were elicited from the questionnaire.

Definitions and descriptive statistics of the farm and farmer characteristics used in the analysis are shown in Table 2.1. The dependent variable is the farmer's response to the statement "manure separation is the right strategy for my farm". Farm plans depend on farmer and farm characteristics (Oude Lansink et al. 2003). Farmer characteristics such as *Age, Successor* and *Education* were among the explanatory variables used in the empirical model. Following earlier empirical studies, it is hypothesized that the age of the farmer is negatively correlated with the decision to adopt. In addition to age, the planning horizon of a farmer depends on the presence of a successor. We hypothesize that having a successor has a positive effect on adoption. The variable successor was expressed as a dummy variable where it takes the value 1 if the farmer has a successor. The average age of the farmer in the survey was 50 and 25% of the farmers had successors. The education level of the farmer, which was expressed as a dummy variable (1 if the farmer had higher education) is also assumed to have a positive effect on adoption. Approximately 7.4% of the farmers had obtained a higher education (professional or university).

Table 2.1 Description, mean and standard deviation of the variables used

Variable	Description	Mean	SD
Dependent variable:			
MSstrgy	Manure separation is the right strategy for my farm (0=disagree, 1=neutral, 2= agree)	0.60	0.69
Farm and farmer characteristics:			
Age	Age of the farmer in years	49.63	9.25
Succ	1 if farmer has a successor	0.25	0.44
Educ	1 if farmer had higher education	0.07	0.26
Size	Farm size in DSU (Dutch size unit)	124.92	68.61
Labor	Labor availability in FTE	1.96	0.72
App1	1 if shallow manure injection technique	0.56	0.49
App2	1 if trailing shoe injector technique	0.22	0.42

The farm characteristics used in the empirical model were *Size, Labor, App1* and *App2*. The size of the farm is one of the frequently used explanatory variables in adoption studies. We hypothesize that the larger the farm, the more likely the farmer is to adopt due to scale advantages. The average number of dairy cows in the sample was 92, while the average for all Dutch farms was 74 (Agricultural Economics Research Institute, 2009). The average size of the farms, expressed in Dutch size unit (DSU), was 124.91. Other farm characteristics used in this study included labor availability, as expressed in FTE (full-time equivalent), and the manure application techniques used on grassland. To account for any potential manure application differences, three techniques were distinguished. The techniques were expressed by two dummy variables, *App1*, where shallow manure injection is used, and *App2*, where the trailing shoe injector is used as the manure application technique. The summary in Table 2.1 indicates that 56% of the farms use shallow manure injection, 22% use trailing shoe injector and the rest uses drag feet (drag bars). The type of application technique is assumed to influence the adoption decision, depending on whether the existing application techniques are also used for separated manure.

The survey collected information on farmers' knowledge of and attitude towards manure separation technology. Table 2.2 shows the 14 statements used in the survey and the proportion of farmers' responses to each of the statements. A variable measuring knowledge about manure separation and future application norms was included. The survey collected information on farmers' attitudes toward the different attributes of manure separation, such as the ability to use nitrogen (N) and phosphate (P) minerals optimally, the attractiveness of the manure products, the cost of manure separation, its environmental friendliness and likelihood to serve as a solution to stringent future application norms. Moreover, information on other alternative strategies, such as reducing the phosphate excretion per animal through feed adjustments or keeping fewer animals per hectare, was collected.

Table 2.2 Knowledge and perceptions of farmers and distribution of responses (%)

	1 Strongly disagree	2	3	4	5	6	7 Strongly disagree
1. I am aware of future application norms and legislation (*Know legislation)*	10	6	12	23	21	17	11
2. I know all about manure separation technology (*Know manure separation*)	33	30	12	20	4	1	0
3. I have a clear manure management strategy (*Clear strategy*)	10	14	15	29	14	9	9
4. Through manure separation I can use N and P optimally (*N and P optimum use*)	12	5	6	40	15	15	7
5. Thick fraction is economically attractive (*Thick fraction attractive)*	17	11	6	50	8	3	5
6. Thin fraction is economically attractive (*Thin fraction attractive*)	17	17	5	50	6	5	2
7. The relatively low cost of manure separation is a reason for me to consider manure separation (*Low cost*)	22	18	7	40	8	2	3
8. Future application norms are the reason for me to consider manure separation (*Application norms*)	23	18	5	38	8	5	2
9. I will start manure separation because it is good for the environment (*Good for environment*)	32	18	5	41	1	2	1
10. I find reduction of phosphate excretion by feed adjustment strategy good for my farm (*Excretion strategy*)	11	7	6	33	23	13	8
11. I believe I can still significantly improve manure application on my farm (*Improve application*)	6	5	7	32	27	15	7
12. I believe I can solve the manure problem by keeping fewer animals per hectare (*Keep fewer animal*)	32	11	8	24	10	8	6
13. I have other ideas to solve manure problem (*Other solution*)	9	7	8	44	12	11	10
14. I have not thought about the manure problem (*No thought*)	16	9	9	24	16	8	17

2.5 Empirical results

In this section, we present the results of the factor analysis followed by the results of the SURE model. The results of the ordered probit model, which link the results from the factor analysis and SURE model are then presented.

2.5.1 Results of factor analysis

The factor analysis of attitude variables resulted in 4 factors that, henceforth, are referred to as '*Separation attribute*', '*Knowledge*', '*Other option*' and '*Fewer animals'* based on the factor loadings of the variables on the extracted factors. Table 2.3 shows the factor loadings of attitude variables (in bold) on the extracted factors after a varimax orthogonal rotation. Each of the four factors has an eigenvalue greater than 1. The total variance accounted for is 56%, which is regarded as satisfactory in the social sciences (Hair et al., 1995; Meuwissen et al., 2001).

Table 2.3 Results of factor analysis after varimax rotation

	Factor 1	Factor 2	Factor 3	Factor 4
Know legislation	0.09	**0.75**	0.00	-0.14
Know manure separation	0.27	**0.64**	0.17	0.09
Clear strategy	-0.11	**0.74**	0.29	-0.07
N and P optimum use	**0.53**	0.20	0.28	-0.02
Thick fraction attractive	**0.71**	-0.05	0.16	-0.09
Thin fraction attractive	**0.51**	-0.05	0.37	-0.06
Low cost	**0.80**	-0.01	-0.02	0.00
Application norms	**0.79**	0.08	0.03	-0.22
Good for environment	**0.64**	-0.19	0.02	0.32
Excretion strategy	**0.55**	0.25	-0.14	-0.12
Improve application	0.09	0.02	**0.71**	0.07
Keep fewer animals	-0.07	-0.01	0.03	**0.91**
Other solution	-0.01	0.29	**0.68**	0.04
No thought	0.19	**-0.65**	0.24	-0.22
Eigenvalue	3.19	2.14	1.39	1.12
Cumulative Proportion	0.23	0.38	0.48	0.56
Suggested interpretation	Separation attribute	Knowledge	Other option	Fewer animals

Factor 1, *separation attribute*, has a high loading of variables related to the different attributes of manure separation. The high loading of phosphate reduction by feed alteration (*excretion strategy*) on factor 1 is likely to reflect that the majority of farmers are already using this strategy to reduce phosphate excretion, and they believe they can simultaneously use it with manure separation technology. The seven statements that are loading on factor 1 have a high Cronbach's alpha of 0.79, indicating that they measure the same underlying construct. The second factor, *Knowledge*, has a high loading of variables related to knowledge of manure separation and manure application norms. In addition to these variables, the variable reflecting whether a farmer has a clear strategy for manure management load positively on this factor. While knowledge variables and clear strategy have positive factor loadings, having no thought about manure problems has a strong negative factor loading (-0.65). This indicates that when a farmer believes there is no manure problem and fails to consider the issue, the farmer's knowledge of manure separation and the tendency to have a clear strategy is reduced. The high loading of other solutions and improving manure applications on factor 3 (*Other option)* and of keeping fewer animals on factor 4 (*Fewer animals)* reflects alternative solutions to manure handling and management. Factor 4, *Fewer animals*, has a relatively high loading of the statement which reflects that keeping fewer animals as a solution to manure problem. It is not surprising that keeping fewer animals stands on its own as this solution to the manure problem is different from the other alternative solutions, which try to solve the manure problem without reducing the number of animals.

2.5.2 Results of seemingly unrelated regression estimation (SURE)

For the SURE model estimation, we began our analysis by examining the relationships of each of the four factors obtained in step one with all of the explanatory variables. Before using all the variables in the SURE, a test of the correlation of the explanatory variables revealed that age of the farmer and successor were positively and significantly correlated. The empirical results obtained from the SURE model estimation are summarized in Table 2.4. The F tests of the significance of the equations as a whole show that the equations for *Separation attribute*, *Knowledge* and *Other option* are weakly significant at 15% critical level, while the equation for *Fewer animals* is not significant at the 10% level.

Results show that variables *Age*, *Educ* and *App2* are significant at the 5% or 10% levels in explaining the attitude of farmers toward the different attributes of manure separation technology. The age of the farmer has a significant and negative effect on the attitude of the farmer. This indicates that younger farmers have a positive attitude toward the different attributes of manure separation technology, *ceteris paribus*. The sign of the variable education level is counterintuitive. We expected that the higher the education level of the farmer, the more positive his attitude toward manure separation technology. Our results, however, indicate that education has a negative effect, thus suggesting that farmers with higher education do not have a positive attitude toward manure separation technology, *ceteris paribus*. Variables related to manure application techniques were expressed by two dummy variables, *App1*, where shallow manure injection is used, and *App2*, where trailing shoe injector is used, as manure application techniques on grassland. Our results show that

App2 is significant at the 5% level and is positively related to attitude of farmers. This suggests that farmers who are more experienced in operating the trailing shoe injector technique have a positive attitude toward manure separation technology.

Considering the equation for *Knowledge*, variables *Successor* and *Labor* are significant at the 5% level while *Education* and *Size* are significant at the 10% level. Having a successor, which signifies a longer time horizon, has a significant and positive effect on *Knowledge.* The education level of the farmer is positively related to the knowledge the farmer has about manure separation and the future application norms. The size of the farm also has a positive effect on knowledge of the farmer.

Results of the equation for *Other option* show that only the variable *App2* is significant at the 5% level and is negatively related to *Other option*. This indicates that farmers who are using the trailing shoe injector technique are less likely to consider other options to improve their manure application and handling system.

Table 2.4 Parameter estimates and z-values (in parenthesis) of SURE model

Variable	Separation attribute	Knowledge	Other option	Fewer animals
Intercept	0.51 (0.93)	-0.01 (-0.03)	-0.05 (-0.17)	-0.28 (-0.92)
Age	-0.02 (-1.97)**			
Successor		0.57 (2.30)**	0.27 (1.08)	-0.35 (-1.37)
Educ	-0.64 (-1.73)*	0.53 (1.42)*	-0.02 (-0.04)	-0.20 (-0.53)
Size	-0.001(-0.35)	0.003 (1.78)*	-0.001 (-0.10)	-0.001 (-0.55)
Labour	0.20 (1.14)	-0.38 (-2.12)**	0.09 (0.54)	0.19 (1.04)
App1	0.37 (1.50)	0.12 (0.51)	-0.07 (-0.30)	0.25 (1.00)
App2	0.54 (1.91)*	0.08 (0.29)	-0.66 (-2.28)*	0.34 (1.14)
R^2	0.08	0.07	0.08	0.04

* Significant at 10% critical level.
** Significant at 5% critical level.

Results of the equation for *Fewer animals* show that the size of the farm and successor (significant at 12%) both have a negative effect on *Fewer animals*. This suggests that farmers with successors are less likely to consider reducing the number of animals per hectare as a solution to manure problem.

The goodness of fit of the SURE model is assessed by examining the R^2 for individual equations. A value ranging from 0.04 to 0.08 is found, which is rather low, indicating that the explanatory power of the model is low. One might argue that the implication of these low R^2 values is that, at standard levels of significance, there is no relationship between attitudes and farmer characteristics, and, hence, little is lost by including the attitudes themselves rather than the residuals from the SURE regressions. To check if the SURE is important and its use is justified, we re-estimated the ordered probit model but used the actual attitudes, not the residuals, to determine if it has any impact on the significance of the coefficients. The results from the re-estimated model found a change in significance of the coefficients for age and application type, which were significant with the SURE model (see Table 2.5) but not significant when the actual attitudes (without SURE) are used. Hence, the use of the SURE model is justified and is important in extracting the idiosyncratic attitudes of the farmers.

2.5.3 Results of ordered probit model

The results of the ordered probit model estimation are presented in Table 2.5. Examining the results of the farmer and farm characteristics revealed that the *Age* of the farmer is significant at the 5% critical level with a negative effect on the probability of farmers considering manure separation as the right strategy for their farm. A negative coefficient in age suggests that the probability of manure separation as the right strategy decreases with an increase in age i.e. young farmers are, *ceteris paribus*, more likely to consider manure separation technology as the right strategy for their farm. The parameter for education is negative (critical at 17%), indicating that farmers with a higher education are less likely to think that manure separation is the right strategy for their farm. *Size*, though not significant at the 10% level, is positively related to the probability of manure separation as the right strategy (critical at 20%), indicating that the propensity of farmers to have plans to adopt manure separation technology increases with the size of the farm. The parameter for *Labor* is not significant at the 10% critical level, while the parameters for *App1* and *App2* are significant at the 5% level with a positive effect on the strategy to adopt variable. The type of application technique is assumed to influence the adoption decision depending on whether the existing manure application systems can also be used for separated manure. The positive effect of the application dummy variables on strategy to adopt reflects the farmer’s belief that existing manure application equipment could be used for separated manure.

Table 2.5 Parameter estimates of ordered probit model

Variable	Coefficient	Z-statistics	P > /Z/
Age	-0.041**	-2.44	0.015
Educ	-0.744	-1.37	0.172
Size	0.003	1.19	0.234
Labour	-0.219	-0.82	0.413
App1	1.239**	3.16	0.002
App2	1.135**	2.63	0.009
Attribute- residual	1.635**	2.63	0.000
Know-residual	-0.019	-0.14	0.888
Other-residual	0.189	1.14	0.255
Fewer animals-residual	-0.476**	-3.18	0.001
Cut1	-0.96**		
Cut2	1.18**		
Number of observations	111		
Log likelihood	-59.90		
LR χ^2	93.60		
Prob> χ^2	0.000		
Pseudo R^2	0.44		
Count R^2	0.80		

*significant at 10% critical level.
**significant at 5% critical level.

Model results pertaining to the idiosyncratic attitudes of the farmers revealed that the parameters for the *Attribute-residual* and *Fewer animals-residual,* which denote, respectively, the idiosyncratic attitudes related to the different attributes of manure separation and the belief that keeping fewer animals per hectare as an alternative solution to the manure problem, are significant at the 5% critical level. *Attribute-residual* has a positive effect while *Less-residual* has a negative effect. A positive coefficient in *Attribute-residual* indicates that farmers with a positive attitude toward the different attributes of manure separation technology are likely to consider manure separation as the right strategy for their farm, whereas the negative coefficient in *Fewer animals-residual* indicates that the propensity of a farmer to consider manure separation as the right strategy decreases if the farmer considers reducing the number of animals per hectare as an alternative solution to the manure problem. The residuals from the *Know* and *Other option* equations, which represent the idiosyncratic attitudes of farmers toward knowledge of manure separation and other options to manure problem, do not have any obvious effect on the likelihood of farmers to consider manure separation as the right strategy for their farm. This suggests that the fact that a farmer has knowledge about manure separation technology does not have any effect on the probability that the farmer has a strategy to adopt manure separation technology. Hence, knowledge is not expected to be the determining factor for future adoption.

Cut1 and Cut2 in Table 2.5 are the estimated cut-off points. In our ordered probit model, there are two cut-off points to distinguish three groups (0, 1, 2). To assess whether three different attitude levels can be distinguished, we check whether the two cut-off points are significantly different from each other. Considering the 95% confidence bound of Cut1 and Cut2 revealed that the mean value of Cut1 (-0.96) is outside the 95% confidence interval for Cut2 and vise-versa, suggesting that both cut-off points are significantly different.

The likelihood ratio Chi-square test in Table 2.5 provides a test for the hypothesis that all predictors' regression coefficients in the model are simultaneously equal to zero. The p-value from the LR test, 0.000, leads us to reject the null hypothesis and conclude that at least one of the regression coefficients in the model is significantly different from zero.

The goodness of fit of the ordered probit model is assessed using McFadden's R^2, which is given by $McFadden\,R^2 = 1 - \log L_1 / LogL_0$ where log L_0 is the maximum value of the log-likelihood function when all parameters, except the intercept, are set to zero, and log L_1 is the maximum value of the log-likelihood of the model without constraints. The McFadden R^2, as shown in Table 2.5, is 0.44, indicating that the model's predictive power is good. An alternative way to evaluate the predictive power of the model is to check the count R^2 which is calculated by comparing the actual and predicted outcomes (see Table 2.6). The benefit of the cross-tabulation of actual and predicted outcomes is to compute the percentage of correct predictions based on the model versus naive predictions based on a model with an intercept term only. The predictions for the farmer's attitude toward manure separation as the right strategy are correct in 80% of cases (i.e., 50+34+5= 89). A correct prediction is when the model predicts 0 (disagree) and it actually was or, likewise, when it predicts 2 (agree) when the decision was 2. If one were to make a naive prediction, the correct prediction rate would be the largest category, that is, 0 (57) and the correct prediction rate would be 51%. Therefore, the model provides a good increase in correct predictions (29%) when compared to naive predictions.

Table 2.6 Cross-tabulation of actual and predicted outcomes

Actual MSstrategy[1]	Predicted probability MSstrategy			Total
	Disagree (0)	Neutral (1)	Agree (2)	
Disagree (0)	50	6	1	57
Neutral (1)	4	34	3	41
Agree (2)	0	8	5	13
Total	54	48	9	111

[1]Response to the question "Manure separation is the right strategy for my farm"

The marginal effects of all independent variables are presented in Table 2.7. The marginal effects indicate, for example, that a one year increase in age decreases the probability of considering manure separation as the right strategy by 0.001. The marginal effects also illustrate that a higher score in the attitude toward the different attributes of manure separation technology increases the likelihood of considering manure separation as the right strategy.

Table 2.7 Marginal effects of the ordered probit model on the probability of manure separation as the right strategy

Variable	Marginal effects		
	Probability (disagree)	Probability (neutral)	Probability (agree)
Age	0.016	-0.015	-0.001
Educ	0.260	-0.250	-0.011
Size	-0.001	0.001	0.001
Labour	0.086	-0.080	-0.006
App1	-0.453	0.416	0.037
App2	-0.426	0.355	0.070
Attribute-residual	-0.644	0.599	0.046
Know-residual	0.008	-0.007	-0.001
Other-residual	-0.075	0.069	0.005
Fewer animals-residual	0.187	-0.174	-0.013

2.6 Discussion and conclusions

Technologies for manure separation are well researched and ready for use in practice. Their use, however, has been limited to the Netherlands. The purpose of this study was to identify the factors that determine the probability of a farmer having a strategy to adopt manure separation technology. The results of this study are useful for policy makers, technology developers and distributors in identifying what determines the decision-making behavior of farmers. The approach used in this study enables policy makers and technology developers to identify and target those farmers who most likely adopt the technology in the future.

This study tested the hypothesis that a farmer’s attitude toward technology-specific attributes condition his intention to adopt manure separation technology. In analyzing this relationship, we also investigated the role that farm and farmer characteristics play in influencing the attitudes of the farmer towards the different attributes of manure separation technology. Three steps were followed to estimate the probability of a farmer having a strategy to adopt manure separation technology. The factor analysis resulted in 4 factors, namely, *separation attribute*, *knowledge*, *other option* and *fewer animals*. Results from SURE showed that a farmer’s attitude towards manure separation technology is significantly affected by the farmer’s age and education level. The farmer’s knowledge about manure separation and future strategy is significantly determined by the presence of a successor, education level, size of the farm and labor availability. Other options for handling the manure problem were not significantly affected by farm and farmer characteristics. Results from the ordered probit model indicated that the probability that a farmer has a strategy to adopt manure separation technology was negatively affected by the farmer’s age. The type of manure application technique had a positive effect. The other characteristics, education level (significant at the 17% level) and size (significant at the 20% level) were weakly significant in the model. When considering farm and farmer characteristics, we conclude that young farmers with a low level of education and bigger farm size are more likely to adopt manure separation technology in the future.

Our results showed that a farmer’s attitude towards the different attributes of manure separation technology are important determinants of the strategy to adopt the technology. Farmers with a positive attitude are likely to consider manure separation as the right strategy for their farm, whereas farmers who are considering reducing the number of animals as a solution to the manure problem are less likely to consider manure separation as the right strategy for their farm. Our results further showed that the probability that a farmer has a strategy to adopt manure separation technology is not affected by the farmer’s level of knowledge about the technology.

The results from this study are not directly comparable to studies on the adoption of technologies as this study is an *ex ante* analysis of technology adoption. Comparable studies are Oude Lansink et al. (2003), who identified factors that affect the strategic planning of pig farmers and Breustedt et al. (2008), who assessed farmers’ willingness to adopt genetically modified oil seed-rape. Moreover, our results are in line with those of Adesina and Zinnah (1993) and Adesina and Baidu-Forson (1995), who showed that the farmer’s perception of technology-specific attributes significantly affect adoption behavior. Our results also found that the farmer’s attitude towards the different attributes of manure separation technology is an important determinant in the farmer’s strategy to adopt the technology.

The analysis in this study is based on survey data of dairy farmers. Although the analysis captured key farm and farmer characteristics and the differences in attitudes, the analysis was unable to capture differences in the type of livestock farms. Moreover, data related to the financial position of the dairy farm were not included in the analysis due to the inaccessibility of the data. Surveys that capture such differences by conducting a survey among pig farmers and by including financial data would strengthen subsequent analyses.

Furthermore, while traditional adoption studies deal with determinants of adoption behavior, it is also important to examine the non-adoption of the technology (Adesina and Baidu-Forson, 1995).

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Chapter 3

Economic Analysis of Anaerobic Digestion- A case of Green Power Biogas Plant in the Netherlands

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NJAS- Wageningen Journal of Life Sciences (2010) 57: 109-115

Abstract

One of the key concerns of biogas plants is the disposal of comparatively large amounts of digestates in an economically and environmentally sustainable manner. This chapter analyses the economic performance of anaerobic digestion of a given biogas plant. A scenario analysis is carried out based on a linear programming model to identify feedstocks that optimize electricity production and to determine the optimal application of digestate. The economic analysis is based on net present value (NPV) and internal rate of return (IRR) valuation criteria. In addition to a default scenario, management and policy scenarios are investigated. The economic results of all the scenarios, except the no subsidy scenario, show positive NPV. The highest NPV and IRR values are observed under the scenario with reverse osmosis (RO) as a green fertilizer. Our findings show that treating RO as a green fertilizer, as opposed to manure (default scenario), is not only lucrative for the plant but also lessens the environmental burden of long distance transportation of concentrates. This chapter concludes that given the uncertainty of regulations concerning RO and the currently low values of digestate and heat, investments in anaerobic digestion technologies are not profitable unless subsidies are provided.

Key words

Anaerobic digestion, biogas plant, reverse osmosis, linear programming

3.1 Introduction

Manure residues from livestock industries have long been identified as a major source of environmental pollution. Traditionally, these wastes have been disposed of, directly or after composting, as soil amendments in the agricultural industry. Since this practice has resulted in the degradation of air, soil and water resources, new regulations for protecting the environment have been promulgated to control land application of animal manure (Van Horn et al., 1994). The Nitrate Directive, regulates the input of nitrate on farmland, aiming to protect the ground and surface water environments from nitrate pollution and includes rules for the use of animal manure and chemical fertilizers (Henkens and Keulen, 2001). In principle, not more than 170 kg of animal manure N may be applied per ha per year, as long as this is not in conflict with the application standard for total P (Schroder and Neeteson 2008). The implementation of these environmental measures entails a high cost of manure disposal for livestock farmers, which impairs the profitability of farming. As such, livestock industries and regulatory agencies are seeking alternatives for managing manure residues in an economically feasible and environmentally friendly manner. Several studies have shown that anaerobic digestion (AD) of organic wastes has the potential to manage these problems in a cost effective and environmentally sustainable manner (Borjesson and Berguld, 2006; Weiland, 2006; Amon et al., 2007; Murphy and Power, 2008).

Interest has recently been growing in using the anaerobic digestion of organic waste of farm origin, such as manure, crop residues and organic residues from food and agro-industries, to generate renewable energy (Weiland and Hassan, 2001; Braun et al., 2002). Processing manure to biogas through AD recovers energy that contributes no net carbon to the atmosphere and reduces the risk from pathogens from land spreading, as thermophilic or mesophilic AD with a sanitization step destroys all or virtually all pathogens (Holm-Nielsen, 2004).

Besides biogas, AD produces digestate, which consists of a mixture of liquid and solid fractions. Applying digestate to the land is the most attractive option in terms of environmental issues, because it allows nutrients to be recovered and reduces the loss of organic matter (Gomez et al., 2005). A reliable and generally accepted means of disposing of the comparatively large amounts of digestate produced is of crucial importance for the economic and environmental viability of a biogas plant (Borjesson and Berglund, 2006). Murphy and Power (2008) investigated biogas production utilizing three different crop rotations to optimize energy production and performed a sensitivity analysis for a change in the price of digestate. Georgakakis et al. (2003) developed an economic evaluation model based on the concept of NPV to assess the cost effectiveness of biogas production systems fed with pig manure. However, a complete economic analysis of anaerobic digestion, incorporating outcomes from the production and application of digestates is still lacking.

The aim of this study is to analyse the economic performance of anaerobic digestion of a given biogas plant. A scenario analysis is carried out on the basis of a linear programming (LP) model to identify feedstocks that optimize electricity production and to determine the optimal application of digestate. Green power biogas plant located in the northern part of the Netherlands forms the basis for our analysis. The plant is a relatively large plant with an installation capacity of 70,000 tons of input on an annual basis. The plant produces electricity, heat, and three types of digestates, namely fixed fraction (FF), ultra filtration (UF) and reverse osmosis (RO).

This chapter is organized as follows. Section 3.2 introduces the case study and elaborates on the general framework, the data and the assumptions made for developing the optimization model. Section 3.3 provides the model results. The final section contains the discussion and major conclusions.

3.2 Materials and methods

3.2.1 Case study description

Green power biogas plant was established in 2007 by 50 swine farmers, with an installation capacity of 70,000 tons of input on an annual basis. The total investment cost of the plant is € 6.75 million, which accounts for the combined heat and power (CHP) unit, decanter, dryer, land and silos. The important starting point for the plant was its commitment to process a contracted amount of pig manure from its member farmers. The installation, in addition to pig manure, uses other co-digestion materials, such as poultry manure, energy maize, food waste, and flower bulbs. A schematic overview of the Green power AD process is given in Figure 3.1.

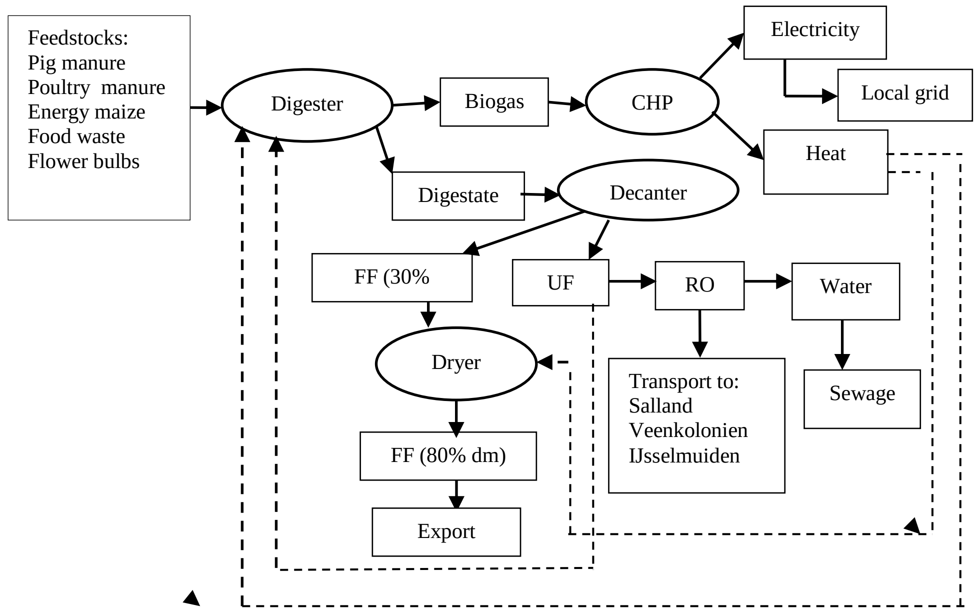

Figure 3.1 Schematic overview of Green power AD process

The feedstocks are mixed, grinded, and pumped to two pre-fomenters of 600 m^3 each. The fermentation starts, and the mixture stays a week in these silos. This pre-fermented product flows to the main fermenter of 1800 m^3 and stays there for 40 days at 40 degrees. The biogas is burned in a combined heat and power (CHP) unit to generate electric power and heat. The electricity produced is sold to the local grid at a market price of 0.06 €/kwh. Additionally, the plant receives an MEP[1] (Environmental quality of electricity production) subsidy of 0.097 €/kwh for a duration of 10 years, after which plant managers estimate that the plant receives about half of the current tariff. The plant is limiting electricity production to a total of 2 MW/year, the amount for which the subsidy is provided.

Market for heat is currently non-existent. The heat is utilized within the plant for heating the digester and drying the digestate. Besides biogas, the plant produces digestate, which is separated into a solid and a liquid fraction via pressing. The fixed fraction (FF), 80% dry matter and rich in phosphate, contains NPK of 9.3, 19.2 and 5.9 kg/ton respectively. The FF concentrate is targeted for export to EU countries with a phosphate deficiency. The plant sells FF concentrate at zero price, but the transportation cost is fully

[1]The MEP (Environmental quality of electricity production) is a kwh subsidy paid to domestic producers of electricity from renewable sources and CHP who feed into the national grid. The state guarantees the subsidy for a maximum of 10 years.

paid by buyers. The ultra-filtration (UF) is recycled to the digestion process, guaranteeing sufficient dilution of the substrate fed into the digester. The Reverse osmosis (RO), also referred to as green fertilizer, contains NPK of 6.8, 0.6 and 11.5 kg/ton respectively. It is used as a supplement to animal manure on plots with low K qualities. Currently, the RO is treated as animal manure, competing with other types of manure with an application rate limited to 170 kg (or 250 kg on grassland) N per ha per year from animal manure. However, pilot projects are underway to test the fertilizing value and treatment of RO as a replacement of artificial fertilizer.

For biogas plants, the first consideration in digestate management is adhering to the hygiene requirements and certification of digestate. Organic waste contains infectious matters, which result in new spreading of pathogens and disease transmission between animals, humans and the environment. Therefore, many countries enforce their legislation regarding pathogen control in digestate. At the same time, the European Council has implemented rules and regulations that are mandatory for all the Member Countries (Al Seadi et al., 2006). In the Netherlands, the Food and Consumer Product Safety Authority (VWA) deals with the monitoring of the production and certification of digestates.

3.2.2 Description of target regions for RO

The RO-concentrate is transported to Salland, Veenkolonien and IJsselmuiden, regions that are relatively near the plant. The key decision parameters for the target regions are land availability, land usage, soil type, crops grown and distance from the plant. Salland, a region with a total surface land area of 51,621 ha, 10-15 km from the plant, consists mostly of sandy soil (CBS, 2006). Arable land comprises of only 7% of the total utilized agricultural area, with grains holding the greatest share of arable land.

Veenkolonien, unlike Salland, consists mostly of arable land, which covers 76% of the total agricultural land. Approximately 60% of the soil in Veenkolonien is peat, and most of the area is used for starch potatoes. Veenkolonien, 60 km from the plant, is characterized as a region with a net deficiency in mineral availability, with around 80% of the fertilizable land in the year 2006 using nutrients (CBS, 2006).

IJsselmuiden, 35 km from the plant, covers an area of 14,140 ha (CBS, 2006). Like Salland, the region is a typical cattle region with a lot of grassland (91%). The conventional arable crops (potato, sugar beet, wheat) play quite a small role as shares of the total fertilizable arable land. A relatively large part of the fertilizable ground is occupied by horticulture; horticulture in greenhouses in particular accounts for around 30%.

3.2.3 Model description

After specifying a set of decision variables and constraints, linear programming (LP) is used in this study to maximize the profit of the plant from sales of electricity and digestate application. A standard LP model with a profit-maximizing objective is expressed as:

$$\begin{aligned}
&Maximize\ Z = \sum_{j=1}^{m} c_j Y_j \\
&Subject\ to: \\
&\sum_{j=1}^{m} a_{ij} Y_j \le b_i \quad i = 1 \ldots N \\
&Y_j \ge 0 \qquad\quad j = 1 \ldots M
\end{aligned} \tag{3.1}$$

where Y is vector of activities, c_j is gross margin per unit of activity j, a_{ij} is technical coefficients and b_i is availability of resource i.

Since digestate comprises of a large percentage (by volume) of the final product from AD, the sustainability of the plant depends on not only maximizing profits from electricity but also on the effective management of digestate. The activities identified as relevant for the current study are, producing and selling electricity and digestates, transporting feedstocks to the factory, hiring people, transporting RO to target regions and storing digestates (see Appendix 3A for LP model specification).

The constraints are the treatment capacity of the plant and digestate application. The capacity constraint is that the total feedstock processed should not exceed the maximum treatment capacity of the plant. The total quantity of digestate transported to regions must be less than or equal to the amount of digestate available. Moreover, the model assumes cognizance of the nutrient content of the concentrate as well as the nutrient uptake of crops per each type of soil in each region. Hence the total amount of nutrients transported to a certain region should be less than or equal to the maximum nutrient uptake capacity of that region. The total digestate storage at the end of each time period is the difference between the digestate available and the total digestate applied to regions. We assume that all the concentrates are transported and thus there is no digestate in storage.

To analyse profitability of the system, net present value (NPV) and internal rate of return (IRR) concepts are used as valuation criteria. NPV is the sum of expected net cash flows measured in today's currency and is given by:

$$NPV = -I + \sum_{t=0}^{n} \frac{CF_t}{(1+r)^t}$$

and (3.2)

$$CF_t = p_t O_i - v_t X_t - FC$$

where *CF* is expected cash flow at time *t*, *r* is discount factor and *I* is initial capital investment cost. *CF* is a function of income (p_t) from *i* outputs (O_i) i.e. electricity, heat and digestate; variable costs (X_t) are feedstock cost, operating and maintenance costs, disposal costs of digestate and water and *FC* is all fixed costs such as labour cost, interest expense and overhead cost. IRR is discount rate for which total present value of future cash flows equals cost of investment.

3.2.4 Model parameterization and assumptions

Total investment cost is € 6.75 million, which accounts for CHP unit, decanter, dryer, land and silos. Investment is paid from own equity capital (15%), investment grant (15%) and remainder is financed from debt assuming a 6% interest rate. It is assumed that average life-span of the plant is 20 years. Subsidy level of 0.097 €/kwh for 10 years and half the current subsidy for the remaining 10 years is assumed. Discount rate of 10% is assumed. Total labour cost, RO transportation cost, operating and maintenance cost and overhead costs are subjected to an average annual increase of 2% .Operating and maintenance costs are maintenance of digester, CHP unit and decanter. Overhead costs are indirect costs such as salary of management, insurance cost and accountancy. Income tax is not considered in our analysis.

Table 3.1, derived from the plant's records shows the current proportion and cost of each feedstock in the total feedstock digestion of 67,500 tons/year. Feedstock composition is a major factor affecting methane yield. Biogas is produced from a broad range of feedstocks which can be solid, slurries, and both concentrated and dilute liquids. However, in the current study, the model only considers the feedstocks currently used by the plant, but it varies the proportion of feedstocks in the total mixture to see how the methane yield varies with feedstock mixture. Fees received are designated as a reduction to costs and are therefore negative.

Table 3.1 Cost and proportion of feedstocks in the total mixture (default scenario)

	tons/year	Feedstock proportion (%)	Fee received (€/ton)	Cost including transportation (€/ton)	Net cost €/ton
Pig manure	49,275	73	-14	2.5	-11.5
Energy maize	7,425	11		38	38
Food waste	3,375	5		40	40
Poultry manure	6,075	9	-14	0	-14
Flower bulbs	1,350	2	0	0	0
Total feedstock	67,500				

The specific characteristics and methane yield of feedstocks are estimated from the literature. The potential production of biogas is directly related to the volatile solids (VS) content. For the purpose of this study, the methane productivity of pig manure, 0.356 m^3/kg VS (Table 3.2), was taken from a study done by Moller et al. (2004). Amon et al. (2007) developed the methane energy value model, which estimates methane yield from the nutrient composition of energy crops via regression models. Although different studies show different methane yields, in this study the methane yields, 0.39 m^3/kg VS of energy maize and food waste of 0.5 m^3/kg VS, are taken from a study done by Amon et al. (2004).

One of the most important parameters describing plant efficiency is organic degradation rate (Lindorfer et al. 2007). Organic degradation rate measures the feedstock degradation efficiency. It is expressed as a percentage of VS. We assume degradation rate of 80% of VS input for Green power due to the plant's short retention time. The design of a biogas plant is directly linked to its hydraulic retention time (HRT), which is defined as the time period during which the mixture of feedstocks stays in the digester to produce the biogas (Singh and Singh, 2004). Green power maintains a short retention time of 40 days to ensure that the continuous supply of pig manure from its member farmers is accommodated. Typical retention time of biogas plants which use energy crops together with manure and organic wastes are between 60 and 90 days (Weiland, 2006). The calorific value of biogas depends on its CH_4 content. It is estimated that 1 m^3 CH_4 = 10 kwh (Amon et al., 2007) and electrical efficiency is assumed to be 37% (Holm-Nielsen, 2004).

With the given digestion process, total feedstocks yield about 60,750 tons of digestate that is further processed to produce FF, UF and RO concentrate. These concentrates account for about half the total volume, whereas remaining fifty percent becomes water that is expelled into sewage at a cost of € 1 per m^3. Composition of digestate depends on feedstocks and therefore the NPK content varies. However, the plant provides tailor-made concentrates as per the needs of farmers. Composition of RO concentrate therefore stays the same.

Table 3.2 Methane yields of feedstocks specified as dry matter (DM) and volatile solid (VS) content [1]

Input	DM %	VS % of DM	Methane yield $m^3\,kg^{-1}$ VS
Pig manure	5-8	80	0.356
Energy maize	35-39	35	0.39
Poultry manure	10-30	80	0.41
Food waste	10	80	0.5
Flower bulbs	10	80	0.5

[1]Sources: Moller et al.(2004); Amon et al. (2004); Amon et al. (2007)

There are three types of mineral application standards: one for total P (sum of mineral fertilizer and organic manure), one for plant available N (sum of mineral fertilizer and N becoming available after application of manure) and one for N in the form of animal manure (Schroder and Neeteson, 2008). When RO is treated as animal manure, application rate is limited to 170 kg/ha (250 kg on grassland). When RO is treated as a green fertilizer, application standard for mineral fertilizers applies. We assume that 5%, 20% and 15% of the total hectares allocated to arable and grassland in Salland, Veenkolonien and Ijsselmuiden, respectively are available for RO application. All farms, arable and grassland, are potential buyers when RO is treated as a green fertilizer. Whereas, only arable farms are potential buyers when RO is treated as manure (the default scenario). Artificial fertilizers are used by both arable and grassland, but most dairy farmers with land apply their own manure, hence we excluded them from potential buyers under the default scenario. The expected selling price of RO as a mineral fertilizer is 5 €/ton (excluding transportation costs) otherwise, the plant pays 20 €/ton for its disposal as animal manure. This is because, the plant is based on digestion of pig manure and most pig farms do not have sufficient land to apply the digestate and hence the plant pays to dispose of the digestate.

Logistics of feedstocks and digestate are important determinants for biogas system to be economically, environmentally and socially viable. Some authors indicate a viable maximum distance of 15-25 km (Poliafico and Murphy, 2007). Long distance transportation is not only costly in terms of transportation cost but also entails environmental costs such as GHG emissions and odor noises. Therefore, the impact of these transport movements should be minimized. The plant is a relatively large plant producing large quantity of digestate and is situated in an area with mostly pig farms, which do not have sufficient land to apply the digestate on. Thus, the plant transports digestate to as nearby farms as possible but at the same time taking nutrient uptake capacity of the regions into consideration. Total transportation and sampling cost of RO to Salland, Veenkolonien and Ijsselmuiden is 3 €/ton, 4 €/ton and 4 €/ton respectively.

3.2.5 Description of scenarios

Two groups of scenarios, management and policy scenarios, are investigated in addition to the default scenario. The default scenario is a model of the given situation; the proportion and price of feedstocks digested are as shown in Table 3.1. The plant receives an MEP subsidy for electricity production and heat is used within the plant. RO is considered to be animal manure with a disposal cost of 20 €/ton. The FF is exported to other EU countries.

The management scenarios analyse the impact of a change in the proportion of feedstocks and price per ton of feedstock, mainly energy maize, on methane yield and overall profitability. The objective of investigating these scenarios is to identify the feedstock mixture that results in a better economic performance. The quantity of pig manure digested remains constant under all scenarios (as shown in Table 3.1). Three scenarios are investigated namely less poultry manure scenario, less food waste scenario and lower maize price scenario. Under less poultry manure scenario, the percentage of energy maize digested is increases to 15% whereas the poultry manure is reduced to 5%. Under less food waste scenario, the percentage of energy maize is increased to 15% while the food waste is reduced to 1%. The lower maize price scenario examines the impact of lower maize price on the profitability of the plant. Currently the plant pays 38 €/ton for energy maize. In consultation with plant experts maize price of 28 €/ton is assumed under lower maize price scenario.

The policy scenarios are two-fold, focusing on RO selling options and the MEP subsidy. In the RO scenario, the RO concentrate is considered as green fertilizer. We analyse the application (transportation) of the concentrate to the target regions and the resulting economic performance. A scenario with no MEP subsidy is investigated to assess the plant's performance in the absence of a subsidy.

3.3 Results

3.3.1 Technical results of scenarios

Table 3.3 presents technical results of default and alternative scenarios, showing electricity yield, feedstock cost per unit of electricity produced, transportation of concentrates and shadow prices of feedstocks and capacity. Results show that under default scenario electricity yield is 222.30 kwh/ton of feedstock digested. Less poultry manure and less food waste scenarios result in slightly higher yields of 224 kwh/ton and 227 kwh/ton respectively than default scenario. Less poultry manure scenario results in a higher yield than default but results in a higher feedstock cost per unit due to a higher cost of energy maize. This indicates that the increase in yield is not high enough to result in lower feedstock cost per unit of electricity. Less food waste scenario has a higher yield because energy maize and poultry manure have higher dry matter content than food waste and hence higher yield. Considering the cost of feedstock, the unit feedstock cost stays the same under the default and less food waste scenario. This suggests that increasing energy maize to 15% in the total mixture results in higher yield without increasing the feedstock cost. Under lower maize price scenario, a 26% reduction in energy maize price results in a 31% reduction in feedstock cost per unit of electricity.

Under the default and management scenarios, where RO is considered as an animal manure, the regulation on N in the form of animal manure applies. Under default scenario, 75% of the total RO concentrate is transported to Veenkolnien, 19% to Salland and 6% to IJsselmuiden. Most of the RO is transported to Veenkolonien because the region comprises mostly of arable land. Moreover, the regional data of Veenkolonien reveals that approximately 80% of the fertilizable land already uses nutrients, while the remaining 20% is regarded as a potential application area, which makes the region more attractive for transporting RO compared to the other regions that have limited nutrient uptake capacities.

The RO as green fertilizer scenario results in transporting all the concentrate to Salland. Apart from the relatively lower transportation cost to the region, the deciding factor for transporting all the concentrates to Salland is that both arable and grassland are considered as potential buyers.

Table 3.3 Technical results of Green power for default and alternative scenarios

	Default	Management scenarios			Policy scenario	
		Less poultry manure	Less food waste	Lower maize price	RO as green fertilizer	No subsidy
Electricity yield (kwh/ton)	222.30	224.00	227.00	222.30	222.30	222.30
Total electricity (million kwh)	15.00	15.12	15.32	15.00	15.00	15.00
Digestate FF (ton/year)	8000	8000	8000	8000	8000	8000
Digestate UF (ton/year)	14000	14000	14000	14000	14000	14000
Digestate RO (ton/year)	10327	10327	10327	10327	10327	10327
Water (m3/year)	34000	34000	34000	34000	34000	34000
Feedstock cost (ct. €/kwh)	-1.57	-0.63	-1.57	-2.06	-1.57	-1.57
RO Transportation (tons):						
Salland	1913	1913	1913	1913	10327	1913
Veenkolonien	7739	7739	7739	7739	0	7739
IJsselmuiden	675	675	675	675	0	675
Shadow prices (€):						
Pig manure	36.54	36.54	36.54	36.54	36.54	21.07
Poultry manure	75.80	75.80	75.80	75.80	75.80	37.62
Energy maize	30.58	30.58	30.58	40.58	30.58	-11.79
Food waste	10.24	10.24	10.24	10.24	10.24	-20.80
Flower bulbs	50.24	50.24	50.24	50.24	50.24	19.20
Capacity	38.38	36.57	39.19	39.48	38.38	16.81

The shadow prices of all feedstocks remain the same under all the scenarios except under the no subsidy scenario. Under the default scenario, poultry manure has the highest shadow price of € 75.80 and € 37.62 without subsidy. The shadow price suggests that a 1 ton increase in poultry manure results in an increase in gross margin of € 75.80 under default scenario. Flower bulbs and pig manure are the next feedstocks with high shadow prices. This is attributed to the fact that these feedstocks have high gate fees (pig manure and poultry manure) or are acquired at zero cost (flower bulbs). Food waste has the lowest shadow price. Without subsidy, energy maize and food waste have significantly lower and negative shadow prices, implying that increasing these feedstocks is not economical. The shadow price of capacity indicates that a 1 ton increase in capacity results in an increase in gross margin of € 38.38 under the default scenario. The shadow prices are important decision parameters, as they allow decision makers to determine whether certain potential changes in the given situation actually increase profitability.

3.3.2 Economic results of scenarios

Table 3.4 shows net present value (NPV) and internal rate of return (IRR) for all of the scenarios investigated. The economic results follow from the technical results. Economic results shows that under the default scenario, NPV is € 4.20 million and IRR is 21%. Given the subsidy level, the less poultry manure scenario resulted in the lowest NPV due to higher total feedstock costs. The RO as green fertilizer scenario resulted in the highest NPV (€ 6.27 million) as a result of increased revenues from selling RO as a green fertilizer. In the no subsidy situation, the plant operates under a loss and a substantial decline in NPV and IRR (showing a negative value) is observed, implying that investments in anaerobic digestion of manure with a CHP unit are not profitable unless subsidies are provided.

Table 3.4 Economic results of Green power for default and alternative scenarios (€1000)

	Default	Management scenarios			Policy scenarios	
		Less Poultry manure	Less Food waste	Lower maize price	RO as green fertilizer	No subsidy
Revenues						
Sales of electricity	900	907	919	900	900	900
Sales of RO	-206	-206	-206	-206	52	-206
Sales of FF	0	0	0	0	0	0
MEP subsidy	1,455	1,467	1,486	1,455	1,455	0
Total revenues	2,148	2,167	2,199	2,148	2,407	694
Costs						
Pig manure	-566	-566	-566	-566	-566	-566
Poultry manure	-85	-47	-85	-85	-85	-85
Energy maize	282	384	384	208	282	282
Food waste	135	135	27	135	135	135
Flower bulbs	0	0	0	0	0	0
Total feedstock cost	-234	-94	-240	-309	-234	-234
Total labor cost	166	166	166	166	166	166
RO transportation	39	39	39	39	31	39
Water disposal	35	35	35	35	35	35
O and M[1] cost	220	220	220	220	220	220
Interest	255	255	255	255	255	255
Depreciation	337	337	337	337	337	337
Overhead[2]	175	175	175	175	175	175
Total cost[3]	993	1134	988	919	985	993
Operating profit	1155	1034	1211	1229	1406	-300
NPV[4]	4195	3233	4592	4770	6267	-5499
IRR	21%	19%	22%	22%	25%	0%

[1]Operating and maintenance costs are inclusive of maintenance for digester, CHP unit and decanter
[2]Overhead cost includes indirect costs such as salary of management, insurance cost and accountancy
[3]Total labor cost, RO transportation cost, O and M and overhead costs are subjected to an average annual increase of 2%
[4]Assuming discount rate of 10%, discounted over 20 years

3.4 Discussion and conclusions

This paper analysed the economic performance of the anaerobic digestion of a given biogas plant. A scenario analysis was carried out based on a linear programming (LP) model to identify feedstocks that optimize electricity production and to determine the optimal application of digestate. The economic analysis was based on the concepts of NPV and IRR to assess the cost-effectiveness of the biogas system.

The default scenario resulted in an electricity yield of 222.30 kwh/ton of feedstock digested. Increasing energy maize in the total feedstock mixture from 11% (default scenario) to 15% (less food waste scenario) resulted in a 2% increase in yield. The less poultry manure scenario resulted in the highest feedstock cost per unit whereas the unit feedstock cost stays the same under the default and less food waste scenario.

Our findings showed that the number of tons of reverse osmosis (RO) transported to regions and the distance transported are different under the default and the RO as green fertilizer scenarios. The concentrate stayed closer to the plant when it is treated as green fertilizer, thus resulting in lower transportation costs and presumably less environmental impact. Therefore, treating RO as a green fertilizer is not only profitable for the plant but also lessens the environmental burden of long distance transportation of concentrates. Moreover, it results in saving of energy consumption for the production of chemical fertilizers.

A synthesized economic evaluation of all scenarios except the no subsidy scenario showed a positive NPV. The highest NPV value is observed under the RO as green fertilizer scenario. This is attributed to the increased revenues from selling RO as a green fertilizer and the reduced transportation cost of concentrates. The no subsidy scenario resulted in a negative NPV, implying that the subsidy plays a great role in the profitability of the biogas plant.

The economic analysis done in this study was based on a number of assumptions. The estimated methane yield of feedstocks was generated from the literature as the plant is in its starting up phase, and a reliable estimate of technical performance was not obtained. To insure that technical performance is not overestimated, values for yield were corrected by 80% due to the plant’s short retention time. The investment costs accounted for in the study include land value, which, in the given situation, is treated as agricultural land as opposed to an industrial segment. The average price for an industrial segment is more than six times the average price for agricultural land (Segeren and Luijt, 2002). The lower price of land overestimates the economic performance relative to when the land is treated as an industrial segment. Because there is not much long-term experience using digesters in Netherlands, the project life is uncertain. However given its size and design, it is assumed that a well-designed and maintained digester have a project life of 20 years.

The implementation of this environmentally friendly technique depends widely on a political framework that creates and provides an economically attractive incentive for running anaerobic digestion plants. Dutch renewables policy has been widely criticized for having been too unstable to provide sufficient incentives for investments in renewable energy technologies (Van Rooijen and Van Wees, 2006). The uncertainty in receiving subsidies makes a highly cost-efficient system important. Our recommendations for biogas plants to be profitable without a subsidy is to look for alternative revenues, for instance, from digestate and heat or from savings in feedstock costs by entering into a contract with arable farms to supply them with RO concentrate in return for less expensive energy crops. In conclusion, given the uncertainty of RO treatment regulations and the currently low values of digestate and heat, investment in anaerobic digestion of manure and other co-substrates is not profitable unless subsidies are provided.

The analysis based on an LP model yields useful insights into the relative performance of a biogas plant and demonstrates the implications of two distinct selling options in relation to RO-concentrate. However, our study can further be extended to incorporate and address uncertainties associated with estimating methane yields, subsidies and the price of digestates.

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Appendix 3A. LP Model formulation

$$Max\ Z = ES + ROS - TLBC - OMC - \sum_{I=1}^{n} BM_i \times Cbm_i -$$
$$ROTC - ROSC - FFTC - FFSC \qquad (A.1)$$

$Subject\ to:$

$$MP = \sum_{i=1}^{n} BM_i \times VS_i \times Y_i \qquad (A.2)$$
$$EP = MP \times Tcoeff_e \qquad (A.3)$$
$$D = Tcoeff_d \times TBM \qquad (A.4)$$
$$RO = Tcoeff_r \times D \qquad (A.5)$$
$$FF = Tcoeff_f \times D \qquad (A.6)$$
$$\sum_{i=1}^{n} BM_i \le TBM \qquad (A.7)$$
$$BM_i = TBM \times P_i \qquad (A.8)$$
$$\sum_{r=1}^{k} TRO_r \le RO \qquad (A.9)$$
$$STRO = RO - \sum_{r=1}^{k} TRO_r \qquad (A.10)$$
$$STRO \le MSC \qquad (A.11)$$
$$N_r = Tcoeff_n \times TRO_r \qquad (A.12)$$
$$P_r = Tcoeff_p \times TRO_r \qquad (A.13)$$
$$K_r = Tcoeff_k \times TRO_r \qquad (A.14)$$
$$N_r \le \sum_{c=1}^{m} L_{cr} \times Nreq_{cr} \times ROb_r \times ROacc_r \qquad (A.15)$$
$$TLBC = LE + \sum_{d=1}^{j} LD_d \qquad (A.16)$$
$$ROTC = \sum_{r=1}^{k} TRO_r \times tc_r \qquad (A.17)$$
$$ROSC = STRO \times sc \qquad (A.18)$$

Where: Z = gross margin (€)

ES = electricity sales (€)

ROS = reverse osmosis (RO) sales (€)

TLBC = total labor cost (€)

OMC = operating and maintenance cost (€)

BM_i and Cbm_i = tons and cost of feedstock i digested (i = 1 to 5)

ROTC and ROSC = total transportation cost and storage cost of RO (€)

FFTC and FFSC = total transportation cost and storage cost of FF (€)

MP = methane production (m^3)

VS_i = volatile solid content of feedstock i (%)

Y_i = methane yield of feedstock i (m^3/kg VS_i)

EP = electricity generation (kwh)

$Tcoeff_e$ = technical coefficient of generating electricity from $1m^3$ of CH_4

D = total quantity of digestate (ton)

TBM = total quantity of feedstock digested (ton)

$Tcoeff_d$ = technical coefficient of digestate

$Tcoeff_r$ = technical coefficient of RO

$Tcoeff_f$ = technical coefficient of FF

P_i = proportion of feedstock i in the total mixture

TRO_r = RO transported to region r (ton) (r = 1 to 3)

STRO = quantity of RO in storage (ton)

MSC = maximum storage capacity (ton)

Nr = total quantity of N transported from RO to region r (kg) (r = 1 to 3)

P_r = total quantity of P transported from RO to region r (kg) (r = 1 to 3)

K_r= total quantity of K transported from RO to region r (kg) (r = 1 to 3)

L_{cr} = Land available for crop c in region r (ha)

$Nreq_{cr}$ = Nitrogen requirement of crop c in region r (kg/year)

ROb_r = potential RO buyer in region r (%)

$ROacc_r$ = acceptance level of RO in region r (%)

LE = labor cost allocated to electricity (€)

LD_d = labor cost allocated to digestate d (€) (d = 1 to 2)

Tc_r = transportation cost per ton of RO to region r (€/ton)

Sc = storage cost per ton of RO (€/ton)

Chapter 4

Energy-Neutral Dairy Chain in the Netherlands: An Economic Feasibility Analysis

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Biomass and Bioenergy (2012) 36: 60-68

Abstract

The Dutch dairy chain is aiming to achieve energy-neutral production by bringing the whole chain from dairy farm to factory ultimately to be self-sufficient in energy in year 2020, through a combination of wind, solar and biogas. This paper investigates the economic feasibility of producing green gas from digestion of dairy manure and other co-substrates. A simulation model of producing 17 PJ of green gas from two business models, stand alone and central upgrading was developed. Probability distributions are chosen to describe the profitability and risks for individual business models and for the aggregate energy production at dairy sector level. Data sources are from 23 operating biogas plants in the Netherlands. Simulation results show that the probability of a negative net present value (NPV) is less than 50% for both individual models. The probability that the combined business models producing 17 PJ result in a negative NPV is 23%. A total of 109 plants are needed to produce the total energy, requiring 8.5% of the total amount of cattle manure produced in the Netherlands to be processed. Sensitivity analysis based on spearman rank correlation coefficient between NPV and each of the sample input distributions show that biogas yield and investment costs have significant effect in determining the NPV values.

Key words

Anaerobic digestion, biogas, green gas, Monte Carlo simulation

4.1 Introduction

Nations nowadays are investing in new technologies and new sources of energy that leave less of an environmental 'footprint' than coal or oil, and that are more sustainable (Young, 2005). Anaerobic digestion (AD) of organic wastes and by-products from agriculture and food industry is a process known for many years and is widely used for waste stabilization, pollution control, improvement of manure quality and biogas production (Weiland, 2006). Biogas production from manure contributes to pollution reduction by reducing emissions of CO_2 via substitution of fossil fuels, and by reducing methane (CH_4) emissions from manure during storage (Moller et al., 2007). In EU, where only about 5% of gross energy consumption is made up of renewables, which is lower than that observed in many parts of the world, the share of renewables is expected to double by 2010, and the share of biogas, as a part of it, is expected to rise to 12%, according to the white book of the EU-Commission from 1997 (Nielsen and Al Seadi, 2006). The Dutch government’s goals in its white paper on energy call for a simultaneous approach of continuous energy savings, efficiency improvement of 30% (Kwant, 2003) and a 20% share of renewable energy in 2020 (EREC, 2008).

In addition to initiatives at EU and national levels, there are sector initiatives to produce and utilize green energy. For instance, glasshouse owners in the Netherlands are looking at biogas production as an alternative to natural gas and as a solution to keep energy costs under control. The Dutch dairy chain is aiming to achieve energy-neutral production i.e. bringing the whole chain from the dairy farm to the factory ultimately to be self-sufficient in energy in year 2020, possibly by a combination of wind, solar and biogas. This initiative is part of its broader sustainable dairy chain initiative which focuses on making the entire chain sustainable in the context of three major themes: energy and climate, animal welfare and biodiversity. The sector aims to achieve this by working together with dairy farmers and chain partners to improve energy efficiency, reduce the emission of greenhouse gases and stimulate the production of sustainable energy on dairy farms. There are pilot projects throughout the dairy chain to invest in production facilities such as digestion plants to convert manure and other co-substrates into biogas. That way the dairy farmer, not only delivers milk to the processing factories but also green energy.

This chapter assesses the economic feasibility of producing green gas from anaerobic digestion of dairy manure and other co-substrates in the Dutch dairy chain. Total energy consumption in the Dutch dairy chain is 60 PJ. This study, however focuses on the part of direct energy consumption which is envisaged to be produced from biogas systems.

Direct energy consumption (milk production and processing) is estimated to be 25 PJ per annum i.e. excluding energy footprints in feed and artificial fertilizers. Out of the direct energy consumption, the dairy sector aims to produce 17 PJ from biogas systems and the remaining from a combination of wind and solar energy. In this paper, we first develop possible biogas business models, then for each business model we perform investment appraisal and finally determine the economic feasibility of the aggregate energy production (17 PJ) at dairy sector level.

One of the major considerations in deciding upon investment in renewable energy is its profitability. The two most widely advocated valuation methods are the net present value (NPV) and internal rate of return (IRR). There are numerous financial feasibility studies of biogas systems. Georgakakis et al. (2003) developed an economic evaluation model on the basis of NPV to determine the cost-effective size of a centralized biogas system; Svensson et al. (2006) investigated the financial prospects of high-solid digestion at different scales; Gebrezgabher et al. (2010a) investigated the economic performance of a biogas plant based on a linear programming model; Karellas et al. (2010) developed an investment decision tool for biogas production and Gebrezgabher et al. (2010b) estimated the costs and profits of producing 25 PJ of green energy from dairy manure and other co-substrates. The results of these studies indicated the importance of choosing substrates with a high methane yield, the investment costs, biomass acquisition costs, subsidies and the market value of the end products (electricity, heat and compost) as important determinants of economic viability of the system. These studies provide an insight into the important determinants of the feasibility of biogas systems. However, inherent in these studies is the deterministic nature of the analysis. Feasibility studies based on a deterministic output value do not adequately account for uncertainties surrounding key variables such as investment costs, biogas yield, conversion efficiency and prices of co-substrates. In this study, we explicitly account for risk by developing a stochastic simulation model in which variables such as investment costs, biogas yield, conversion efficiency and price of co-substrates vary within certain ranges. In addition to that, the contribution of this study compared to other studies that tend to use theoretical biogas yields is that, the analysis is based on technical and financial data from 23 biogas plants operating in the Netherlands. This enhances the economic analysis of biogas systems by improving the available data on biogas systems.

The remainder of this chapter is organized as follows. Section 4.2 provides a brief review of biogas systems in the literature. This is followed by a discussion of materials and methods in section 4.3 and results, in section 4.4. Section 4.5 concludes.

4.2 Review of literature on biogas systems

Interest in biogas plants in Netherlands and other European countries arose in the late 1970s and early 1980s following the oil crisis (Raven and Geels, 2010). As a consequence, many fermentation plants were built, particularly in Denmark and Germany with capacity varying from 10,000 tons of biomass/year to around 150,000 tons/year. In 2001, Denmark had 20 centralized biogas plants in operation in which up to 100 farmers cooperate while in Germany the number exceeded 1500 with almost all digesters being small scale, single farm facilities (Raven and Geels, 2010). A study on economic performance of centralized biogas plants in Denmark showed that most of the plants produced a current income at or above the break-even income (Hjort-Gregersen, 2003). In 2006, there were 30 biogas plants in operation in the Netherlands. The biogas plants have a capacity of processing 2000-4000 tons/year (for a single farm) up to around 36,000 tons/year as the regulation on maximum capacity allowed for a single farm is up to around 36,000 tons/year (Wempe and Dumont, 2008).

To date, almost all biogas produced worldwide is used for electricity (approximately 35% efficiency) and heat (around 60% efficiency) production in a combined heat and power unit (CHP) (Borjesson and Mattiasson, 2008). The heat produced is only partly (around 35% used to heat the plant itself) used. The remainder cannot always be used locally and is often released into the air, thus resulting in a reduction of energetic efficiency from 90% to 65% (Vries and Van Burgel, 2005). The alternative route with much higher energy utilization efficiency is to convert the biogas into natural gas. There are various technologies that upgrade biogas into green gas. The most common upgrading technologies are the water scrubber and the pressure swing adsorption (PSA) technology (Jonson, 2004). The main step in upgrading is the separation of carbon dioxide from the methane gas. When the gas is fed to the grid, meeting the required Wobbe index or heating value of the gas usually requires a 97% methane (Persson et al., 2006). Table 4.1 shows an overview of technical and financial data of upgrading biogas at varying scales.

The data in Table 4.1 are derived from feasibility studies except the study by Dirkse (2007) which reported data from an operating plant in Tilburg, Netherlands. Results of the different feasibility studies showed varying conversion efficiencies, investment and production costs. Conversion efficiency for upgrading biogas varies from 62% to 80%. The variation in investment cost for upgrading plant is from 0.20 €/m^3 to 0.38 €/m^3 and production cost from 0.13 €/m^3 to 0.27 €/m^3. The variation in technical and financial data is due to variations in the upgrading processes assumed in the study.

Table 4.1 Overview of technical and financial data of upgrading biogas

	Unit	Dirkse (2007)	Hullu et al. (2008)	Stoomer (2008)	De Veth (2008)	Wempe and Dumont, (2008)
Production (million)	m^3	4-5	1	4-5	4-5	4-5
Technical data:						
Conversion efficiency	%	70	80	62	67	80
Financial data:						
Investment	€/m3	0.60[1]	0.22[3]	0.38[3]	0.24[3]	0.20[3]
Production cost[2]	€/m3	0.14	0.13			0.27
Depreciation	Year	15	10	10[4]	12	

[1]Digestion and upgrading plant.
[2]Utilities such as electrical power, water and chemicals excluding cost of feedstock.
[3]Upgrading plant only.
[4]10 year for upgrading plant and 20 years for gas pipe.

4.3 Materials and methods

4.3.1 Business models

To produce green energy by the dairy chain, two possible business models were identified in consultation with different experts from a number of institutions. The role of the experts is to identify which business models are best suitable to realize the energy-neutral initiative while data from 23 operating biogas plants are used to evaluate the profitability of the business models. The first institution approached was Rabobank which is active in financing investment in renewable energies. Based on the type of existing biogas systems currently financed by the financial institution and based on new developments, two existing models (CHP farm and CHP large scale) and two new models (stand alone green gas and central upgrading model) were first identified. The CHP models generate electricity and heat while the stand-alone and central upgrading models generate green gas.

Key considerations in deriving the business models were heat utilization, feedstocks digested and size of plants. Heat produced by biogas plants should be properly utilized to get permits and to qualify for a subsidy. Proper heat utilization is described as avoiding of excessive flaring of heat to the air. Moreover, the regulation on maximum capacity allowed for a single farm is up to around 36,000 tons/year. To check the plausibility of the assumption on possible business models, experts from the Dutch ministry of Economic Affairs, Agriculture and Innovation (EL&I), Senternovem, a dairy processing company and the experimental biogas plant “De Marke” who are involved in studies related to renewable energy were approached. As the prospects of an upgrading plant are better compared to a CHP unit because of its potential to avoid excessive loss of heat to air and the new higher subsidy per m^3 of green gas, the two business models are, stand-alone and central upgrading model.

Table 4.2 Description of business models

	Stand-alone	Central upgrading
Annual production	4-5 million m^3	5-6 million m^3
Organization	Stand-alone plant	Two farm-scale biogas plants and central upgrading
Investments	Digester Gas improver Digestate separation	Digester Gas improver Digestate separation
Input	50% manure 50% other (energy maize, grass silage and other co-substrates)	50% manure 50% other (energy maize, grass silage and other co-substrates)
Output	Green gas Digestate (thin fraction and thick fraction)	Green gas Digestate (thin fraction and thick fraction)

Table 4.2 shows the business models. The two business models upgrade biogas into natural gas but they differ in their organization. The central upgrading model has two farm scale digestion plants supplying biogas to a central upgrading plant while in the stand-alone model, the digestion and upgrading of biogas is done in one plant. The business models have production capacity of 4-6 million m^3 of green gas. The total green energy (17 PJ) is assumed to be produced by a combination of the two business models with 50% share each. The substrate mixture comprises of 50% cattle manure and 50% other co-substrates (15% energy maize, 10% grass silage and 25% other) in both models. This substrate composition, which is comparable with the farm-scale operating biogas plants in the Netherlands (see Table 4.3) and assuming that fermentation takes place at mesophilic temperatures results in an average biogas yield of 118 m^3/ton of feedstock. Digestate is partly (50%) applied on own land. It is assumed that the plants are able to use existing public nets. The new SDE (sustainable energy production subsidy) level for green gas of €

58.30 ct./m^3 is assumed (EZ, 2009). SDE is a follow-up to the former MEP (Environmental quality of electricity production) scheme which subsidizes the exploitation of new sustainable energy projects i.e. production of renewable gas and electricity for a maximum of 12 years.

4.3.2 Profitability and risk analysis

The annual production is given by a transformation function describing the conversion of multiple inputs into multiple outputs.

$$Oi = f(I, B, V, F) \tag{4.1}$$

where O_i = (O_1, O_2) is a vector of outputs with O_1 green gas and O_2 digestate; f is a transformation function; I is the investment cost; B is a vector of feedstocks used in production and $B = (B_1, B_2, B_3, B_4)$ where B_1 is cattle manure, B_2 energy maize, B_3 grass silage and B_4 other co-products; V is a vector of variable costs (V_1,V_2,V_3) where V_1 *is* operating and maintenance cost, V_2 is running cost and V_3 is cost of feeding green gas to grid. F is total fixed costs (start-up cost, labour cost, interest and depreciation).

The annual cash flow (*CF*) is given by:

$$CF_t = P_i O - P_B B - C_v V - FC \tag{4.2}$$

where P_i is vector of price of outputs; P_B is vector of price of feedstocks; C_v is vector of variable costs and *FC* is fixed costs.

The NPV is then given by:

$$NPV = -I + \sum_{t=0}^{n} \frac{CF_t}{(1+r)^t} \tag{4.3}$$

where I is total investment cost and r is the discount rate.

A risk analysis application utilizes information, be it in the form of objective data or expert opinion, to quantitatively describe the uncertainty surrounding key project variables as probability distributions, and to calculate the possible impact of the uncertainty on the return of the project (Savvides, 1994). It suggests the probabilistic modelling of a range of possible values for each parameter and the following reproduction of an efficient number of random scenarios. The synthesis of all the iterations gives a range of possible outcomes (Tziralis et al., 2008). The simulation is performed for k = 1, . . . q iterations, where q is typically larger than 1000, by picking random values from the statistical distributions, such that:

$$NPV = f(A_1 \ldots\ldots A_k) \tag{4.4}$$

where *f* denotes the function defined by the simulation model. A_k with k = 1……q iterations, i.e. the simulation results in a set of *q* NPVs, thus the NPV is described by a particular distribution.

The probability distributions are the basic building blocks for risk models which are concerned with calculating the probability distribution of output random variables based on the probability distribution of input random variables. Hence, we are interested in the probability that the NPV falls within an interval (i.e. probability density function) and the probability that a random variable is less than some value (cumulative probability distribution) (Garlick, 2007). The probability density function is denoted by *p(NPV)* such that:

$$\int_a^b p(NPV)dNPV = pr(a \le NPV \le b) \tag{4.5}$$

4.3.3 Model parameterization

Data were collected from three sources; operating biogas plants in the Netherlands, literature review and expert elicitation. Table 4.3 shows data from the year 2008 on selected parameters of 23 operating biogas plants in the Netherlands. All plants are CHP unit plants under the MEP subsidy and the majority of them started operation in 2006. Although all plants are CHP unit plants, the data provide an estimation of biogas yield, methane content and price of feedstocks which are also relevant in the case of green gas models.

The amount of substrate processed varied between less than 5,000 ton/year in the smallest installation up to 63,000 ton/year in large plants. Most plants (more than 70%) are farm-scale plants with a digestion capacity up to 36,000 ton/year. The biogas yield ranged from 70 to 182 m^3/ton. The majority of the digestion is carried out at mesophicilic temperatures with 2 plants having temperatures greater than 50^{o}C. The lowest electrical efficiency was 31%, while one plant achieved efficiency of over 40%.

Investment costs are total of the whole installation i.e. silos, digester, CHP unit and civil works. Investment cost showed variation among the different plants within their respective scales. The variation in investment cost for small scale plants is from 0.42 to 0.59 €/kwh, for farm scale 0.36 to 0.62 €/kwh and for large scale 0.38 to 0.41 €/kwh. The majority of the plants use cattle manure as the main feedstock with a share of 50% of the incoming materials. Energy maize and grass silage were the dominant feedstocks used for co-fermentation. Other co-digestion materials used are weed, potatoes, vegetables mix, glycerin, solid fraction digestate and expired products from supermarket. There is a wide variation in the price of co-digestion materials among the plants. The variation in price for energy maize is 15 to 35 €/ton, for grass silage 10 to 30 €/ton and for other co-product 8.6 to 58.10 €/ton. The reason for the price variations is that there is no an established market especially for grass silage as farmers trade mutually and prices vary seasonally.

4.3.4 Stochastic and deterministic variables

The NPV that is described as having a certain distribution is derived by taking a sample from each of the input distributions. The model input variables along with their unit of measurement are listed in Table 4A.1 (see appendix 4A). Specified functional forms for stochastic variables are mentioned in third column of the table. From the 23 operating biogas plants, data pertaining to the farm-scale plants are used to define a range of possible value for the stochastic variable, biogas yield since these are representative plants with similar feedstock composition as the business models. Stochastic variables for which the data could not be used to define a probability distribution are modelled based on literature and expert opinion. Historical energy maize prices were obtained from Agricultural Economics Research Institute (2008). For grass silage there is no real market; farmers trade it mutually, directly from selling farmer to buying farmer. The price of cattle manure is assumed to be zero. Variables for which no relevant probability distribution could be identified are modelled in a deterministic way.

Table 4.3 Descriptive statistics of technical and economic figures of operating CHP units (n = 23)

	Capacity (ton of feedstock/year)											
	Small scale Capacity <10,000 ton (n= 4)				Farm scale Capacity = 10,000-36,000 ton (n=17)				Large scale Capacity >36,000 (n=2)			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
HRT (days)[1]	56	15	38	74	39	26	24	109	41	28	21	61
Biogas yield (m^3/ton)	150	26	119	182	118	26	70	169	98	16	86	109
Methane content (%)	57	1	56	57	58	4	52	65	57	1	52	54
Engine efficiency (%)	36	4	31	41	35	2	32	39	36	1	35	37
Investment (€/kwh)	0.49	0.07	0.42	0.59	0.44	0.07	0.36	0.62	0.40	0.02	0.38	0.41
Start up (% investment)	2.00	0.50	1.60	2.70	1.60	0.40	1.40	3.00	1.80	0.40	1.50	2.00
Feed to grid (ct. €/kwh)	0.20	0.02	0.16	0.20	0.15	0.02	0.13	0.21	0.13	0.01	0.13	0.13
Energy maize (€/ton)	27	5	20	30	30	6	15	35	31	1	30	32
Grass silage (€/ton)	20	1	18	20	23	6	10	30	n.a[2]	n.a	n.a	n.a
Other co-product (€/ton)	22.30	22.05	17.40	57.80	19.80	13.03	9.90	58.10	24.95	23.12	8.60	41.30

[1]Median HRT (Hydraulic retention time)
[2]n.a.= not applicable, not used by the plants

4.4 Results

4.4.1 Technical results of business models

Technical results (Table 4.4) are presented in terms of the estimated total tons of feedstocks digested, green gas and digestate produced. Quantity of feedstocks digested under each business model equalled total estimated energy production divided by the energy yield which is stochastic, so quantity is a stochastic variable. Given the estimated average biogas yield and conversion efficiencies as outlined in Table 4A.1, the stand alone model requires 62,000 tons of feedstock with a standard deviation of 15,000 tons while the central upgrading model requires 69,000 tons of feedstock with a standard deviation of 19,000 tons to produce a net green gas of 4.5 million m^3 and 5.5 million m^3 respectively. The quantity of the different forms of digestate is also stochastic as it depends on the quantity of feedstocks digested.

Table 4.4 Technical results of business models[1]

Item	Stand-alone		Central upgrading	
	Mean	SD[2]	Mean	SD
Green gas (million m^3/year)	4.50		5.50	
Total feedstock (1000 ton/year)	62	17	69	20
Digestate-unprocessed (1000 ton/year)	49	14	55	15
Thin fraction (1000 ton/year)	42	12	46	13
Thick fraction (1000 ton/year)	7	2	8	2

[1]5000@Risk iterations.
[2]Standard deviation.

4.4.2 Economic results of business models

To show the total investment costs, revenues and cost components accounted for in our analysis, Table 4.5 presents deterministic economic results of the business models. Total investment costs for the stand alone model is € 3.6 million and for the central upgrading, € 4 million. Investment costs for the central upgrading is total of two biogas plants and a central upgrading. Revenues are total of the base price and subsidy. Total costs are feedstock cost accounting for 31% of the total cost, variable costs accounting for 34%, digestate disposal costs accounting for 12% and the remainder is fixed costs. Both business models resulted in mean positive operating profit and NPV.

Table 4.5 Economic results of business models (€ 1000)

	Stand-alone	Central upgrading
Total investment[1]	3,595	4,015
Total revenues	2,794	3,120
Costs		
Energy maize	317	355
Grass silage	116	129
Other co-products	362	405
Total biomass cost	*795*	*889*
Operating and maintenance cost	191	214
Gas upgrading running cost	672	749
Feed to grid	11	13
Thin fraction disposal	197	220
Thick fraction disposal	122	136
Total variable costs	*1193*	*1332*
Start up	64	72
Labor	140	140
Depreciation	180	201
Interest	197	221
Total fixed costs	581	634
Total cost	*2,569*	*2,856*
Mean operating profit	225	264
Mean NPV[2]	483	678
IRR (%)	12	12

[1]Investment costs are the total of the whole installation i.e. silos, digester, upgrading and civil works.
[2]Discount rate of 10% discounted over 20 years.

Table 4.6 outlines simulation results of the two business models. Results are presented in terms of the expected operating profit, NPV and the probability of economic success for each business model. Results show that the mean operating profit for the stand alone plant is € 0.23 million with a 90% confidence interval ranging from minus € 0.33 million to € 0.95 million and 75% chance of operating profit. The mean NPV for the stand alone plant is € 0.48 million with a 90% confidence interval ranging from minus € 3.7 million to € 5.28 million and more than 50% chance of economic success. The central upgrading model resulted in a mean operating profit of € 0.26 million with a 90% confidence interval ranging from minus € 0.36 million to € 1.08 million and mean NPV of

€ 0.68 million with a 90% confidence interval ranging from minus € 3.95 million to € 5.89 million. The cumulative probability distribution showed that there is more than 75% chance of a positive operating profit and 58% chance of economic success for the central upgrading model.

Table 4.6 Simulation results of business models[1]

	Stand-alone	Central upgrading
Operating profit (€ 1000)		
Mean	225	264
5%	-333	-360
95%	949	1,084
Probability (Operating profit < 0)	0.25	0.23
NPV (€ 1000)		
Mean	483	678
5%	-3,749	-3,954
95%	5,281	5,890
Probability (NPV < 0)	0.46	0.42

[1]5000 @Risk iterations.

4.4.3 Results of up-scaling to 17 PJ

The risk analysis produced estimates of the variability in operating profit and NPV of up-scaling to 17 PJ (Table 4.7). The stochastic analysis projected that the total operating profit is € 22 million with a 90% confidence interval ranging from € 11 million to € 33 million. NPV is projected to be € 37 million with a 90% confidence interval ranging from minus € 53 million to € 122 million. The probability of operating under loss and of a negative NPV for the aggregated business models is 2% and 23% respectively. The estimated number of business models required to produce the 17 PJ is 88 and requires a minimum of 63 (5%) and a maximum of 113 (95%) business models. In terms of number of plants this would be 109, as central upgrading model consists of 2 farm-scale biogas plants. The total number of dairy farms in the Netherlands is 20,746 (CBS, 2008) with a total annual manure production of 35.50 million ton. Considering 50% of the total feedstock is cattle manure, the total amount of manure needed is 3 million tons, which is about 8.5% of the total amount of cattle manure produced in the Netherlands.

Table 4.7 Results of up-scaling to 17 PJ[1]

	Mean	5%	95%
Total number of business models	88	63	113
Operating profit (€ million)	22	11	33
NPV (€ million)	37	-53	122
Probability (operating profit < 0)	0.02		
Probability (NPV < 0)	0.24		

[1]5000 @Risk iterations.

4.4.4 Sensitivity analysis

Sensitivity analysis is important in determining which variables have important effect on the output. Sensitivity analysis in this study is based on spearman rank correlation coefficient between NPV of business models and each of the sample input distributions. Table 4.8 presents the statistically significant correlation coefficients. The higher the correlation between a variable and NPV, the more closely the variation in the variable is associated with the NPV. The correlation coefficient between biogas yield and NPV of the stand-alone model is 0.84 and of the central upgrading the coefficient is 0.88. Investment cost has a significant effect on the outcome of NPV of the business models with a correlation coefficient of -0.40 for the stand alone and -0.26 for the central upgrading.

Table 4.8 Spearman rank correlation coefficient between NPV and input variables

Stochastic variable	Spearman rank (correlation coefficient) NPV	
	Stand-alone	Central upgrading
Biogas yield	0.84	0.88
Upgrading efficiency	0.20	0.20
Investment stand alone	-0.40	-0.26[1]
Energy maize price	-0.15	-0.13
Grass silage price	-0.10	-0.10

[1]Biogas plant only

4.5 Discussion and conclusions

Studying the effects of a possible variation in the value of key decision variables on the financial viability of biogas plants is informative to decision makers such as farmers and managers in the dairy chain who have an interest in the new initiative (energy-neutral dairy chain). Uncertainty in output of interest resulting from uncertainty in the input parameters is studied by a Monte Carlo analysis. A simulation model of producing 17 PJ of energy from 2 business models was developed based on relevant input/output coefficients and the required investment costs. Probability distributions were chosen to describe the risk of obtaining a negative NPV (NPV<0) for individual business models and for the aggregate production of 17 PJ. The aim of the study was not to give investors a final decision, rather to assess the risk profile of the project and thereby facilitate investment decision making. The decision to invest in green gas models therefore, rests to a large extent on investors' attitude towards risk.

Simulation results of individual business models showed that the probability of a negative NPV for the stand-alone green gas model is 46% and for the central upgrading the probability is 42%. The risk analysis also produced estimates of the variability on NPV of up-scaling to 17 PJ. The probability that the combined business models producing 17 PJ result in a negative NPV is 23%. A total of 109 plants are needed to produce the required total energy and 8.5% of the total amount of cattle manure produced in the Netherlands is required to be processed. Sensitivity analysis based on a spearman rank correlation coefficient between NPV of business models and each of the sample input distributions showed that biogas yield and investment costs have significant effect in determining the NPV values.

In addition to looking at the risk profile of green gas production by the dairy chain, it is logical to raise questions, which concern the operationalization of the initiative. Such concerns include availability of feedstocks, location of digesters and availability of subsidy. Published ambitions envision a share of 8–12% of green gas in 2020, 15–20% in 2030 and 50% in 2050. A study on green gas potential based on available feedstock which can be digested showed that co-digestion has a green gas potential of 1500 million m^3 per annum (Wempe and Dumot, 2008). Major share can be produced from co-digestion of manure and agricultural crops. This potential is not yet exploited, nevertheless, if in the long term other food chains become energy-neutral chain, availability of feedstocks (particularly the co-digestion materials) is a bottleneck. In addition to concerns about availability of feedstocks, digesters should be strategically located based on local availability of manure and other feedstocks as long distance transportation of feedstocks hampers the economic and environmental sustainability of the plant. Another concern relates to SDE subsidy granted by the government. The concept of the current SDE subsidy arrangement is that the government determines the base price in such a way that the investor ultimately has an NPV neutral investment opportunity. There are two subsidy related concerns for the farmer, firstly, the subsidy duration is for 12 years while it is assumed that a well-designed and maintained digester has a project life of 15 to 20 years. There is no clear arrangement after the 12 years have elapsed. A scenario analysis assuming 12 years project life showed that the probability of a negative NPV increases to 60% for both business models. Secondly, subsidy funds available are not sufficient for all applications. Funds are allocated on a first-come first-serve basis and in most of the cases funds are oversubscribed. Regarding policy on renewable energy, due to frequent shifts in policy the Dutch government has failed to build confidence in the stakeholders and has failed to reduce market uncertainties (Van Rooijen and Van wees, 2006). Therefore, it is important to conduct further investigations on how to operationalize the initiative.

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Appendix 4A.

Table 4A.1 Stochastic and deterministic variables in the Monte Carlo simulation model

Variable	Unit	Distribution type	Description	Parameterization CHP	Stand-alone	Central upgrading
Technical data						
Biogas yield[1]	m3/ton	Normal	Mean	118	118	118
			SD	26	26	
Biogas to electricity[1]	kwh/m3	Normal	Mean	2.05		
			SD	0.17		
Upgrading efficiency[2,3]	%	Triangular	Minimum		0.62	0.62
			Most likely		0.70	0.70
			Maximum		0.80	0.80
Digestate unprocessed [1]	%	Deterministic		80	80	80
Thin fraction (% digestate)[1,3]	%	Deterministic		85	85	85
Thick fraction (% digestate)[3]	%	Deterministic		15	15	15
Investment costs						
CHP[1]	€/kwh	Normal	Mean	0.45		
			SD	0.07		
Stand-alone [2,3]	€/m3	Triangular	Minimum		0.45	
			Most likely		0.60	
			Maximum		1.20	
Biogas plant[2,3]	€/m3	Triangular	Minimum			0.32
			Most likely			0.42
			Maximum			0.84
Central upgrading[2,3]	€/m3	Triangular	Minimum			0.20
			Most likely			0.22
			Maximum			0.24

(Table 4A.1 continued)

Feedstock and digestate disposal cost						
Cattle manure[1]	€/ton	Deterministic		0	0	0
Energy maize[4]	€/ton	Normal	Mean	36.5	36.5	36.5
			SD	5.17	5.17	5.17
Grass silage[1]	€/ton	Normal	Mean	20	20	20
			SD	5.23	5.23	5.23
Other co-products[1]	€/ton	Deterministic		25	25	25
Thin fraction[3]	€/ton	Deterministic		10	10	10
Thick fraction[3]	€/ton	Deterministic		17.5	17.5	17.5
Operating and maintenance costs						
CHP unit[1]	€ ct/kwh	Deterministic		1.5		
Gas upgrading[2]	€ ct/m3	Deterministic			4	4
Upgrading running cost[2,3]	€ ct./m3	Deterministic			14	14
Feed to gird[1]	€ ct/m3	Deterministic		0.15	0.24	0.24
Fixed costs						
Start-up[1]	% investment	Deterministic		1.6	1.8	1.8
Labor	€ ct/ m3	Deterministic		0.9	3	3
Interest	%	Deterministic		5.5	5.5	5.5
Depreciation	year	Deterministic		15	20	20
Revenues						
Electricity price[5]	€ ct/kwh	Deterministic		15.2		
Green gas price[5]	€ ct/m3	Deterministic			58.3	58.3

[1]Table 2 ; [2]Dirkse, 2007; [3]Hullu et al., 2008; [4]Agricultrual Economics Research Institute (LEI), 2008; [5]EZ, 2009.

Chapter 5

A Multi-Criteria Decision Making Approach to Manure Processing: An Application to the Region Salland

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To be submitted for publication

Abstract

This chapter analyses trade-offs between economic, social and environmental sustainability of manure processing systems taking the animal dense region Salland as a case study. Compromise programming (CP) and Goal programming (GP) are used to evaluate trade-offs between gross margin, GHG emissions, ammonia (NH_3) emissions and land use change, taking decision makers' views of the sustainability criteria into account. Results show that there is a conflict between gross margin and the other three criteria, i.e. the highest gross margin requires high emissions of NH_3, high land use change and low GHG emissions savings. The highest GHG emissions savings require high land use change and the minimum land use change causes relatively low GHG emissions savings. The proposed methodology is a useful tool in assisting decision makers and policy makers in designing policies that enhance the introduction of economically, socially and environmentally sustainable manure management systems.

Key words

Manure processing, sustainability, multi-criteria decision making (MCDM), compromise programming, goal programming, analytical hierarchy process (AHP)

5.1 Introduction

The intensification of livestock operations in the European Union has caused increasing environmental impacts on the soil, the water and the air (Jongbloed and Lenis, 1998). Within the European Union, it is estimated that agriculture contributes 49% of CH_4 emissions and 63% of N_2O emissions (Sommer et al., 2004). Most of CH_4 emissions originate from livestock manure during storage while most N_2O emissions originate from field application of animal manure (Sommer et al., 2004). In order to abate these environmental hazards, a series of environmental regulations and directives have been implemented. The EU nitrate directive aims at reducing water pollution caused by nitrate from agriculture and the EU air quality directive sets limits on the emission of ammonia and nitrogen oxides to the atmosphere (Oenema, 2004). Manure management is becoming increasingly important in order to reduce environmental impacts (Karmakar et al., 2007). Manure management is defined as a decision-making process at all stages, i.e. from collection of manure in animal houses till after field application, that aims to combine profitable agricultural production with minimal nutrient losses from manure (Karmakar et al., 2007; Sommer et al., 2009; Chadwick et al., 2011).

The extent and impact of the manure problems became clear in the 1970s and, especially, the 1980s (Langeveld et al., 2007). The problem is still a pressing issue today as it has long been difficult to implement effective strategies to change manure management practices. Alternative environmentally acceptable disposal routes with potential financial benefits are manure processing technologies that provide energy and manure products (Burton and Turner, 2003; Melse and Timmerman, 2009). However, these alternative manure processing technologies are not without problems. Although the main objective of manure processing is to reduce the environmental impact, not all of the technologies achieve a reduction in pollution (Petersen et al., 2007) and most of the technologies are considered to be too expensive for the livestock farmer to adopt (Burton, 2007). Consequently, a socially acceptable manure management system that simultaneously reduces environmental impacts while accounting for the socio-economic welfare of both farmers and society is needed (De Vos et al., 2002).

Manure management involves a number of stakeholders and decision makers with different and more often than not conflicting perceptions of what is acceptable in the context of sustainable development. Different interest groups attach different values to each of the economic, social and environmental objectives. For instance, for the farmer, keeping manure disposal cost at a minimum is important while for the environmental organizations, reducing environmental impacts is more important. This calls for an integrated approach to modelling manure management systems that encompasses multiple objectives of decision makers. The traditional model of optimizing a single objective function over a set of feasible solutions does not capture the complexity of the decision-making processes. In the presence of multiple and conflicting objectives, multi-criteria decision making (MCDM) methods are appropriate tools to support decision-making (Pohekar and Ramachandran, 2003; Romero and Rehman, 2003).

To evaluate the economic and environmental sustainability of manure management systems and to support decision-making, different types of methods based on either mathematical programming or simulation methods are used. The mathematical programming models are either single objective optimization models or multi-objective programming models. Giasson et al., (2002) used a multi-objective programming model to support decision-making with respect to manure allocation decisions at farm level. Alocilja (1997) developed a compromise programming model for phosphorus management for a dairy-crop operation by simultaneously minimizing excess phosphorus from manure and cost of feed. Stonehouse et al., (2002) used a mixed integer programming model to develop a decision-making tool for assessing the technical, environmental and economic performance of alternative manure-handling systems in the context of a whole farm planning model. Others used a linear programming model to optimize farm profitability by introducing the environmental aspects of manure management as constraints (Hadrich et al., 2008; Gebrezgabher et al., 2010). In addition to mathematical programming models, previous studies have used simulation methods (Stonehouse et al., 2002). Kruseman et al., (2008) developed a micro-simulation model (MAMBO) of livestock and agriculture to model the mineral flows within the sector and the resulting emissions. The simulation model is used as a tool to evaluate policies on non-point source emission. Van der Straeten et al., (2010) developed a simulation model for spatial optimization of manure allocation. The simulation model evaluates the cost efficiency of policy intervention in the manure market. Despite the wide range of studies on manure management problems, the integration of economic, social and environmental criteria, taking decision makers' preferences into account has not been addressed.

The objective of this study is to develop a decision-making tool to assess the economic, social and environmental sustainability of manure processing. This paper examines trade-offs between economic, social and environmental impacts of manure processing and integrates views from different decision makers. The methodology applied in this study can be used as a tool to assist decision makers and policy makers in designing policies that enhance the introduction of economically, socially and environmentally sustainable manure management systems.

The remainder of this chapter is organized as follows. Section 5.2 introduces the MCDM modelling framework. Section 5.3 provides a brief description of manure processing technologies considered in this study, the case study and the data. Results are given in section 5.4. Conclusions and implications are given in section 5.5.

5.2 Modelling framework

MCDM is a well-known branch of decision-making which deals with the process of making decisions in the presence of multiple objectives (Pohekar and Ramachandran, 2003). A complex decision problem usually involves multiple and conflicting objectives. MCDM thus seeks to assist the decision maker in identifying feasible alternative solutions that attempt to reach a balance among the multiple objectives. This task can be formulated as a multi-objective problem by applying a compromise programming (CP) to find the best compromise solution. Figure 5.1 depicts the modelling framework for manure processing systems. First, criteria to measure the economic, social and environmental objectives are determined. By integrating the necessary input information for each of the manure processing considered, a pay-off matrix is constructed to enable decision makers to make trade-offs among the different criteria. After the weights to the criteria that reflect their relative importance are determined, the best compromise solution is computed.

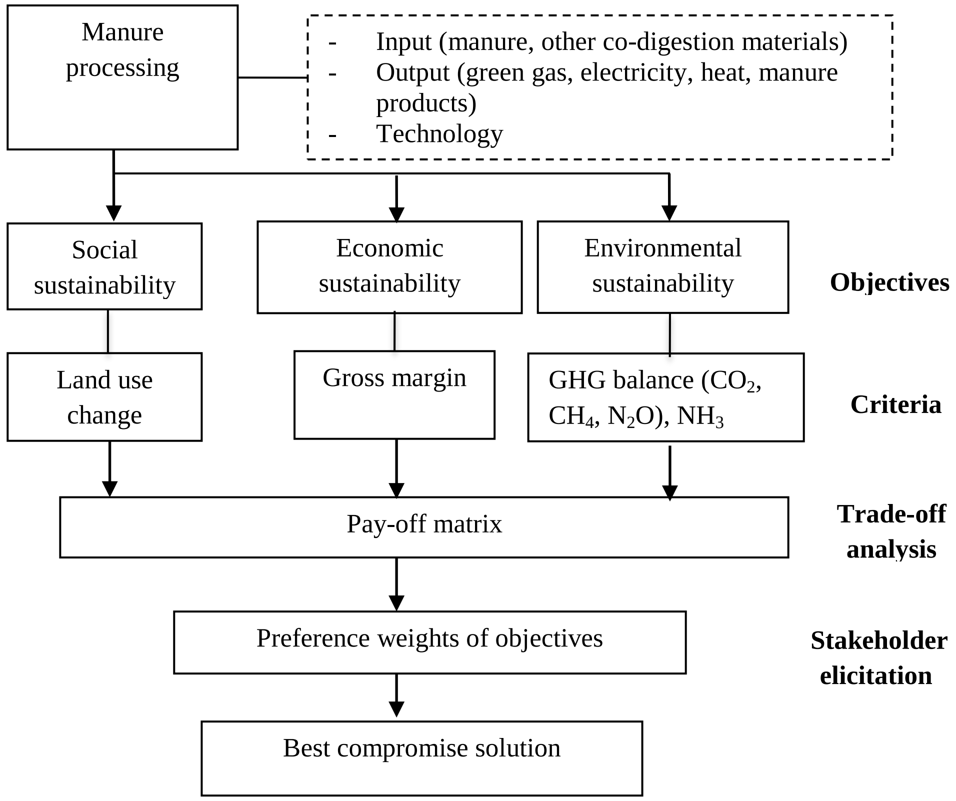


Figure 5.1 Conceptual framework of MCDM analysis of manure processing

5.2.1 Compromise programming

Compromise programming belongs to the class of multi-criteria analytical methods called "distance-based" methods (Romero and Rehman, 2003). It is an extension and a complement to other MCDM technique, the multi-objective programming (MOP) which seeks to solve the problem of simultaneous optimization of several criteria. This is done by identifying the set that contains efficient and feasible solutions for all criteria:

$$Eff\ Z(y) = [Z_1(y), Z_2(y), \dots, Z_n(y)]$$

$$s.t.: \quad F[Z_1(y), Z_2(y), \dots, Z_n(y)] \tag{5.1}$$

where y is a vector of decision variables, $Z_j(y)$ is the mathematical expression for the j^{th} criteria, *Eff* means the efficient solution (minimizing or maximizing) and F is the feasible set.

Compromise programming defines the best solution as the one in the set of efficient solutions with the smallest distance from an ideal point (Zeleney, 1982; Romero and Rehman, 2003). The first step in CP is to construct a pay-off matrix which shows the ideal and anti-ideal values for each of the criteria by optimizing each of the criteria separately over the efficient set. The pay-off matrix shows the degree of conflict between criteria. The ideal point is used as a reference point in CP as the aim is to obtain a solution by choosing a point in the efficient solution which is closest to the ideal value. To achieve this, a distance function is introduced. The normalized distance, d_j, between the j^{th} criteria and its ideal assuming a maximization problem is given by:

$$d_j = \frac{Z_j^* - Z_j(y)}{Z_j^* - Z_{*j}} \tag{5.2}$$

For a minimization problem, the normalized distance is given by:

$$d_j = \frac{Z_j(y) - Z_j^*}{Z_j^* - Z_{*j}} \tag{5.3}$$

where Z_j^* and Z_{*j} are the ideal and anti-ideal values for the j^{th} criteria respectively. The normalization factor is the absolute deviation between the ideal and anti-ideal solution and is used to obtain consistent results when the criteria are measured in different units (Zeleny, 1982).

The final step in generating the compromise set is to select a distance measure. The distance measure between each solution and the ideal point used in CP is the family of L_p-metrics and is given by:

$$L_p(W) = \left[\sum_{j=1}^{n} W_j^p \left[\frac{Z_j^* - Z_j(y)}{Z_j^* - Z_{*j}}\right]^p\right]^{1/p} =$$

$$L_p(W) = \left[\left(\sum_{j=1}^{n} W_j\, d_j\right)^p\right]^{1/p} \tag{5.4}$$

where p is metric defining the family of distance functions which reflects the importance attached to the deviation of each criterion from its ideal value. W_j is the preference weight attached to the j^{th} criterion.

The L_p metrics are used to calculate the distances between solutions belonging to the efficient set and an ideal point. The value $p=1$ implies that all deviations are equally important. As p increases, the larger deviations are given more weights. The general property of the L_p metrics is that L_1 is the largest distance and L_∞ is the shortest distance and hence the possible distance measures are bounded by L_1 and L_∞ metric distances (Romero and Rehman, 2003). Then the compromise solution is chosen so as to minimize d_j. In a bi-objective case metrics p =1 and $p = \infty$ define two bounds of the compromise set and the other best compromise solutions fall between these two bounds (Yu, 1973). For more than two objectives, the L_1 solution implies the maximum aggregate achievement (maximum efficiency) while the L_∞ solution implies maximum discrepancy between achievements of different objectives is minimized. The minimization of a linear combination between the bounds $p=1$ and $p=\infty$ is given by:

$$min\ (1-\lambda)D + \lambda \sum_{j=1}^{n} W_j\, d_j$$

s.t.

$$W_j d_j \leq D \quad j = 1, \dots, n$$

$$F[Z_1(y), \dots, Z_n(y)] \tag{5.5}$$

where D represents the maximum degree of discrepancy. When λ=1, we have the L_1 solution of maximum aggregated achievement and for λ=0, we have the L_∞ solution of minimum discrepancy. For values of λ belonging to the open interval (0,1), we get intermediate solutions (if they exist) which are trade-offs or compromises between the two opposite poles. Therefore, the compromise set can be approximated through variations in the value of parameter λ.

5.2.2 Preference weight elicitation

To implement the CP framework described in the previous section, the preference weights attached to each of the criteria by several social groups should be determined. This is done first by determining individual preference weights from pairwise comparison procedure and then aggregating individual preference weights to obtain group weights.

Elicitation of individual preference weights from pairwise comparisons

Individual decision maker's preferences with respect to a set of criteria is represented by means of a pairwise comparison method in the context of the analytic hierarchy process (AHP) developed by Saaty (1980). The pairwise comparisons are performed by asking decision makers or stakeholders to respond to a series of pairwise comparisons. The pairwise comparisons are made by rating the relative importance on a 9 point Saaty scale ranging from equal importance (1) to absolute importance (9) (Saaty, 1980). The pairwise comparisons are used both to compare the alternatives with respect to the various criteria and to estimate criteria weights (Loken, 2007).

The results from all pairwise comparisons are put into a matrix (PC matrix). This method allows the conversion of qualitative estimates elicited from stakeholders to quantitative estimates. For n number of criteria to be evaluated, there are $n(n-1)/2$ associated pairwise comparisons. From these values, a square matrix $n \times n$ is built and each entry a_{ij} of the square matrix represent the judgement made by the k^{th} stakeholder when the i^{th} criterion is compared with the j^{th} criterion as follows:

$$A = [a_{ij}] = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} \qquad (5.6)$$

It is assumed that elements of the matrix are reciprocal i.e. the comparison matrices comprise paired reciprocal comparisons. If, for example, one criterion is judged to be 5 times more important than another, then the other must be one-fifth as important as the first, i.e.

$$a_{ij} = {}^{1}\!/_{a_{ji}} \quad for\ i \neq j\ and\ a_{ii} = 1, \quad \forall i, j \qquad (5.7)$$

Once the matrix of comparisons of criteria is constructed, the individual preference weights are computed and the consistency of the judgements is determined. An important aspect of AHP is the idea of consistency which is defined as the transitivity between judgements (Saaty, 1980). That is to say matrix *A* is consistent if:

$$a_{ij} \times a_{jk=}a_{ik}\,, \quad \forall i \neq j \neq k \tag{5.8}$$

In practice, however, due to the existence of noise or imperfect judgements, the matrices or judgements might prove to be not perfectly consistent. The question is: what to do with an inconsistent PC matrix from which the final weights are to be computed? Gonzalez-Pachon and Romero (2004) proposed a method with the objective to approximate the original PC matrix. That is, they try to search a consistent and reciprocal matrix that differs from the original PC matrix as little as possible. The result is a new consistent matrix $M = (m_{ij})$ which is a modified version of $A= (a_{ij})$. Following Gonzalez-Pachon and Romero (2004), the following GP model is formulated to obtain a consistent matrix:

Achievement function:

$$Min \sum_{s}(n_s + p_s) + \sum_{r}(n_r + p_r) + \sum_{t}(n_t + p_t)$$

s.t.

$$m_{ij} - a_{ij} + n_s - p_s = 0, \quad s = 1,2,\dots,n(n-1), \qquad (similarity\ condition)$$
$$m_{ij}m_{ji} + n_r - p_r = 1, \quad r = 1,2,\dots,n(n-1)/2, \qquad (reciprocity\ condition)$$
$$m_{ij}m_{jk} - m_{ik} + n_t - p_t = 0, \quad t = 1,\dots,n(n-1)(n-2), \quad (consistency\ condition)$$
$$L \leq\ m_{ij} \leq U\ \forall_{i,j} \tag{5.9}$$

where a_{ij} are the elements of the original matrix, the m_{ij} are the elements of the new consistent PC matrix determined from the GP model, the *L* and *U* are respectively the lower and upper bound values for the elements of the PC matrix. The bounds are imposed to satisfy the scale conditions used in the derivation of the original PC matrix. Thus in the case of Saaty's scale $L = 1/9$ and $U = 9$. The *n* and *p* are the deviation variables. It can be observed that there are three goals to be achieved that correspond to the conditions of similarity, reciprocity and consistency. The aim is to keep as much as the information contained in the original PC matrix but simultaneously holding the reciprocity and consistency conditions. Since it is assumed in our case that elements of the PC matrix are reciprocal, the reciprocity condition is not imposed in the exercise.

After the consistent PC matrix is approximated, the final weights are then obtained from the consistent matrix by adopting a Goal Programming (GP) approach (Linares and Romero, 2002; Gonzalez-Pachon and Romero, 2004). To infer the weights from PC matrix *M*, the following GP model is formulated:

Achievement function:

$$Min \sum_{i=1}^{n} \sum_{j=1}^{n} (n_{ij} + p_{ij})$$

s.t.

$$m_{ij} w_j^{kq} - w_i^{kq} + n_{ij} - p_{ij} = 0, \qquad i, j = 1, \ldots, n, \ i \neq j$$

$$\sum_{i=1}^{n} w_i^{kq} = 1, \tag{5.10}$$

$$w_i^{kq} > 0, \qquad \forall_i$$

where $i = 1, 2, \ldots, n$ criteria to be assessed by $q = 1, 2, \ldots, m$ social groups and w_i^{kq} is the preference weight attached to the i^{th} criterion by the k^{th} member of the q^{th} social group that are determined from the GP model and the n_{ij} and p_{ij} are deviation variables.

Aggregation of individual preference weights

After the individual preference weights are determined, the next step is aggregation of individual weights to derive group weights. The aim is to reach a consensus among the participating decision makers (stakeholders) within one social group on the importance of the criteria (Greening and Bernow, 2004). This is done by searching for a consensus matrix or social preference weights that differ as little as possible from the individual preference weights.

Following the AHP in the previous section let N_q be the number of members of the q^{th} social group, W_i^q be the preference weight attached to the i^{th} criterion by the q^{th} social group. The w_i^{kq} is already computed in the previous step from the individual pc matrix. To determine the W_i^q preference weight attached to the i^{th} criterion by the q^{th} social group, the following goal programming (GP) model is formulated:

Achievement function:

$$Min \sum_{i=1}^{n} \sum_{k=1}^{N_q} (n_{ik} + p_{ik})^{\pi}$$

s.t.

$$W_i^q + n_{ik} + p_{ik} = w_i^{kq} \qquad i \in \{1, \dots, n\}, \;\; k \in \{1, \dots, N_q\} \qquad (5.11)$$

where n_{ik} and p_{ik} are respectively the negative and positive deviation variables measuring the under achievement and over-achievement, between the preference weight attached to the i^{th} criterion by the q^{th} social group (W_i^q) and the weight attached to this criterion by the k^{th} member of the q^{th} social group (w_i^{kq}). π is a parameter representing a general metric and acts as a weight attached to the sum of deviation variables. As π increases, more importance is given to the greater deviation, i.e. the preferences of the individuals that deviate from the average are given relatively higher importance (Yu, 1973; Gonzalez-Pachon and Romero, 1999; Linares and Romero, 2002). For π=1, which we assume in our case, the sum of individual disagreements is minimized and the preference of all individuals is given equal importance (Gonzalez-Pachon and Romero, 1999). Therefore, by formulating and solving q similar models, we get the *(m x n)* W_i^q weights assigned to each criterion by each social group.

5.3 Application to manure processing

This section describes the manure processing technologies considered in this study, the basic model, case study and the data used in the analysis.

5.3.1 Manure processing technologies

Different processing technologies that are based on biological and physical processes have been developed and applied to reduce the emissions of greenhouse gases and ammonia and to produce energy. Technologies considered in this study are manure digestion (anaerobic digestion) and manure separation. Anaerobic digestion is a biological process with potential to allow farmers to adopt more sustainable livestock waste management practices (Masse et al., 2011). The process is known for many years and is widely used for waste stabilization, pollution control, improvement of manure quality and biogas production (Weiland, 2006). Biogas production from manure contributes to reduction of CO_2 emissions via substitution of fossil fuels and by reducing CH_4 emissions from the manure during storage (Moller et al., 2007). The feedstocks used in the digestion are either manure only or a mixture of manure and other co-substrates such as energy crop (silage maize), grass or wastes from food processing companies. The biogas produced in anaerobic digestion is either converted into electricity and heat in a combined heat and power unit (CHP) or is directly upgraded to natural gas standards (green gas). Manure separation produces two fractions: a liquid fraction with a low dry matter and a solid fraction. The purpose of separation is to achieve a solid fraction with a higher fertilizing value and a limited volume that reduces transportation cost of manure disposal.

5.3.2 Basic model

This study evaluates the manure processing options based on four criteria applying the compromise programming model described in the previous section. The criteria that are considered relevant for manure management decisions are:

- i) maximization of gross margin
- ii) minimization of GHG emissions
- iii) minimization of NH_3 emissions
- iv) minimization of land use change

These criteria were subsequently evaluated by selected social groups. The first step in eliciting preference weights is to characterise the decision maker or group of decision makers (Linares and Romero, 2002). For this study four groups of decision makers were chosen, namely, provincial government, farmers, dairy processing company and academic group. Provincial government representatives are important decision makers in manure management practices through their involvement in providing permits for setting up manure processing systems and in providing subsidy to encourage sustainable manure management practices. Farmers are directly involved in manure management on their farm. Dairy processing companies are important stakeholders especially in light of the dairy chain's growing interest to encourage sustainable production systems at dairy farms. For instance, as part of its broader sustainable dairy chain initiative, the Dutch dairy sector is aiming to achieve energy-neutral production by 2020 and invested 250 million Euros in sustainability every year (Gebrezgabher et al., 2012). Researchers (academic group) presumably have a more objective look on manure management. These four social groups are assumed to represent the different and conflicting views of society as a whole.

In this section we briefly describe the main features of the basic model. The structure of the basic model has the form of a standard linear programming (LP) model:

$$Maximize\ \{Z = c'Y\},$$
$$Subject\ to\ AY \leq b\ and\ Y \geq 0$$

where Y is a vector of activities, c is the vector of gross margins per unit of activity or emissions per unit of activity depending on which objective/criterion is optimized; A is the technical coefficients; and b is the vector of right-hand side values.

Maximization of gross margin

One consideration in deciding upon investment in manure processing technology is its profitability. This objective implies the maximization of the annual gross margin of manure processing applied in the region. The gross margin is calculated as total revenues from sales of the output from manure processing minus total costs. Total costs are variable operating and maintenance costs, feedstock costs, digestate disposal costs and fixed costs such as start-up cost, labour cost and depreciation.

$$Z_1 = \sum_{i=1}^{I}\sum_{j=1}^{J} P_{ij}\, Y_{ij} - \sum_{i=1}^{I}\sum_{j=1}^{J}\left(cb_{ij} + om_{ij}\right) Y_{ij} - \sum_{i=1}^{I}\sum_{j=1}^{J} fc_{ij}\, Y_{ij} - \sum_{i=4}^{I}\sum_{j=1}^{J} tc_{ij}\, Y_{ij}^{dig} \quad (5.12)$$

where P_{ij} is the price of output i produced from j technology, Y_{ij} is the quantity of output i produced from j technology, cb_{ij} and om_{ij} are respectively the feedstock and operating cost per unit of output i produced from j^{th} technology, IC_{ij} and fc_{ij} are the fixed cost of j^{th} technology, and tc_{ij} is the transportation cost of digestate (Y_{ij}^{dig}) produced by j^{th} technology.

Minimization of greenhouse gases emissions (GHG)

This criterion measures the total GHG emissions net of avoided CO_2 emission from replacing primary energy by green energy (if applicable). Total GHG are CO_2, CH_4 and N_2O emissions. The latter two are expressed in kg CO_2 equivalent.

$$Z_2 = \sum_{i=1}^{I}\sum_{j=1}^{J} CO_{ij}Y_{ij} - E_p CO_p \tag{5.13}$$

$$E_p = Y_{ij} sf$$

where CO_{ij} is the GHG emissions per unit of output i from j^{th} technology, E_p is primary energy to be replaced (natural gas or electricity), CO_p is emission factor for avoided energy and sf is the substitution factor.

Minimization of ammonia emissions (NH_3)

Another important gaseous emissions from livestock operations is ammonia emissions. This criterion measures the total ammonia emissions from manure processing systems.

$$Z_3 = \sum_{i=1}^{I}\sum_{j=1}^{J} NH_{ij}Y_{ij} \tag{5.14}$$

where NH_{ij} is the NH_3 emissions per unit of output i from j^{th} technology.

Minimization of land use for energy crops

This criterion measures the land required for the production of co-substrate mainly silage maize (if applicable).

$$Z_4 = \sum_{i=1}^{I} \sum_{j=1}^{J} LU_{ij} Y_{ij} \tag{5.15}$$

where LU_{ij} is the land use rate per unit of output i from j^{th} technology.

The constraints of the basic model are manure available for processing, energy demand requirement from biogas in the region and land available for producing the co-substrate silage maize.

Manure availability constraint

The sum of the total amount of manure processed by each technology should be less than or equal to the manure available for processing in the region.

$$\sum_{i=1}^{I} \sum_{j=1}^{J} b_{ij}\, Y_{ij} \leq QB \tag{5.16}$$

where b_{ij} is the manure needed per unit of output i from j^{th} technology and QB is the total manure available for processing in the region.

Demand requirement constraint

The sum of the total renewable energy produced from each technology has to be larger than or equal to the region's energy demand from biogas.

$$\sum_{i=1}^{I} \sum_{j=1}^{J} Y_{ij}^{energy} \geq D \tag{5.17}$$

where D is the energy demand from biogas.

Land availability constraint

The sum of land utilized by each technology has to be less than or equal to the land available for producing energy crop in the region.

$$\sum_{i=1}^{I}\sum_{j=1}^{J} LU_{ij}Y_{ij} \leq L \tag{5.18}$$

where L is the land available for producing energy maize in the region.

5.3.3 Case study

The livestock operations in the Netherlands are characterised by large-scale intensive farms which are mainly concentrated in the eastern and southern part of the country (Melse and Timmerman, 2009). The study area is the region Salland which is found in the eastern part of the Netherlands in the province of Overijssel. The province has large quantities of organic waste from livestock operations which comprise of 1.7 million pigs, 0.63 million cows and 10 million chickens. The province aims to contribute to the national targets of CO_2 emissions reduction by reducing its total emissions by 2200 kilotons by 2020 (Statenvoorstel, 2008). The total CO_2 emissions of Overijssel was 7200 kiloton in 1990 which means by 2020, the province aims to reduce its emissions to 5000 kiloton/year. The province aims to achieve this objective by promoting sustainable energy production (wind, solar and biomass) and energy savings from its industry, housing and transport sector (Statenvoorstel, 2008). The share of emission savings from biomass processing in the total savings is estimated to be 50% which makes manure processing as the main potential emission reduction area. In its sustainable energy policy, the province is promoting the sustainable use of biomass by giving priority to the production of green gas and generation of renewable electricity and heat. The province aims to produce 10% of the total energy demand (128 PJ) from biogas in 2020. This makes manure management planning part of the sustainable energy planning of the province.

Salland, a dominion of Overijssel, with a total agricultural land area of 32,523 ha, consists mostly of sandy soil (CBS, 2010). The region is a cattle and pig dense area with most of the agricultural land area under grassland (utilizing about 23,353 ha) and silage maize (7217 ha). Arable land comprises only 6% of the total utilized agricultural area (1953 ha), with cereals covering the largest share of arable land. The total amount of manure produced in Salland is 1.6 million tons, of which 1.23 million tons is dairy manure.

In consultation with the provincial government, in this study we assume that 50% of the dairy manure is available for processing and that the region Salland produces at least 10% of the target share of biogas in the total energy demand from renewable sources, i.e. 1.28 PJ. This is based on the fact that the province aims to allocate the total renewable energy production to different regions within its dominion depending on the availability of manure and on the share of each region's agricultural holding in the total agricultural land of the province. Salland is animal dense region covering about 14% of the total agricultural land in Overijssel. Therefore, the 10% share (1.28 PJ) is assumed as the target share for Salland.

5.3.4 Model parameterization and assumptions

The data used in the development of the basic model was gathered from different sources (see appendix 5A for details). Technical and economic data pertaining to anaerobic digestion option are from operating biogas plants in the Netherlands while technical and economic data pertaining to manure separation are based on Melse and Verdoes (2005). Environmental data are from life cycle assessment (LCA) studies (Zwart et al., 2006; Van der Voet et al., 2008; De Vries et al., 2010). Regional data are from official statistics of the Netherlands (CBS, 2010).

The feedstock for manure separation is manure, while the feedstock for digestion can either be manure or a mixture of manure and other co-substrates. Energy maize and grass silage are the dominant feedstocks used for co-substrates. Based on existing plant performance of biogas plants in the Netherlands, co-digestion of manure yields 118 m^3 of biogas per ton of feedstock digested assuming that the feedstock mixture comprises of 50% cattle manure and 50% other co-substrates (Gebrezgabher et al., 2012). Digestion of manure as the only feedstock results in biogas yield of 22.5 m^3 per ton of manure based on data from demonstration project of "De Marke" (Kool et al., 2005). Feedstock and digestate transport have a significant effect on the economic and environmental performance of the system. Transport of feedstocks (such as maize and food waste) from source is done by a truck with an average distance of 20 km for CHP system and 40 km for upgrading system while for manure separation and manure only digestion, the processes for manure production and conversion are on the same site and thus transport of feedstocks is minimized (Van der Voet et al., 2008).

The SDE (sustainable energy production subsidy) level for green gas of € 58.30 ct./m^3 and for green electricity of € 15.2 ct./kwh is assumed (EZ, 2009). SDE is a follow-up to the former MEP (Environmental quality of electricity production) scheme which subsidizes the exploitation of new sustainable energy projects, i.e. production of renewable gas and electricity. Total costs are feedstock costs, operating and maintenance costs, digestate disposal costs and fixed costs (start-up cost, labour cost, depreciation and interest). Straight-line depreciation is used assuming investment life of 15 years for co-digestion and manure separation, and 10 years for manure only digestion. Investment and operational costs of manure separation technology are based on Melse and Verdoes (2005). The digestate, the manure product resulting after digestion or separation, is transported and applied to fields as animal manure with a total disposal cost of € 5/ton.

Environmental indicators selected in this study are CO_2, CH_4, N_2O, and NH_3. Gaseous emissions were expressed in CO_2-eq using conversion factors of 1, 21, 310 for CO_2, CH_4 and N_2O respectively (IPCC, 2001). Total GHG emissions represent emissions from handling and storage of manure, emissions from handling and transporting of co-substrates (if applicable), and emissions from storage and application of digestate. These calculations of the total GHG emissions expressed in CO_2 equivalent are based on a number of studies (Melse and Verdoes, 2005; Amon et al., 2006; Zwart et al., 2006; Van der Voet et al., 2008; De Vries et al., 2010; Zwart and Kuikman, 2011). In the case of manure digestion, GHG emissions savings are deducted from the total emissions from the system as energy produced from the system will replace fossil energy and thus resulting in emission savings. It is therefore important to know how much primary energy use is avoided due to the energy content of the renewable energy. Ammonia emissions are expected to occur when applying digestate due to a higher level of mineral nitrogen (Amon et al., 2006). Total ammonia emissions represent ammonia emissions during production of co-substrate (if applicable) and emissions during storage and application of digestate (Kool et al., 2005; Melse and Verdoes, 2005; Amon et al., 2006; Zwart, 2006; Clemens et al., 2006; De Vries et al., 2010).

5.4 Results

This section presents results of the MCDM models. First we present the results of the pay-off matrix and trade-offs among the four criteria considered. The results of the preferential weights aggregation from PC matrices are then presented. Finally the results of the compromise programming model are presented.

5.4.1 Pay-off matrix and trade-off analysis

As a first step in the search for optimal manure management strategy, the pay-off matrix is generated for the four criteria. The pay-off matrix is useful in pointing out the degree of conflict among the criteria considered. Table 5.1 shows the pay-off matrix that shows the ideal and anti-ideal values for each of the criteria considered. The ideal values are obtained by optimizing each criterion separately over the constraint set while the other criteria act as constraints. The 4 x 4 square matrix shown in Table 5.1 is obtained by solving four LP problems. The first row of the pay-off matrix for example shows the values of the criteria obtained from the maximization of gross margin while the last row shows the values of the same criteria obtained from minimization of land use change. The elements of the diagonal represent the ideal values for each criterion where all criteria achieve their optimum values while the underlined values represent the anti-ideal (nadir) value for each criterion.

The pay-off matrix shows that there is a conflict between the economic, social and the environmental criteria. This conflict is especially evident between gross margin on the one hand and NH_3 emissions and land use change, i.e. the maximization of gross margin implies high emissions of NH_3 and high land use change and vice versa. The value for GHG emissions (which is minimized) is calculated as GHG emissions from the system net of GHG emissions savings. The savings from the system are more than the emissions from the system and hence we have a negative outcome for GHG emissions (GHG emissions savings). This is in line with the outcomes of studies by De Vries et al., (2010) and Zwart and Kuikman (2011) on environmental performance of co-digestion in Netherlands. The outcomes from these studies showed net negative GHG emissions due to the replacement of fossil based energy by green energy. The ideal value is therefore the highest absolute value which means the highest net GHG emissions savings. Considering the two gaseous emissions criteria, the highest savings in GHG emissions is achieved with a level of NH_3 emissions around 11% higher than its minimum level. There is a strong conflict between GHG emissions savings and land use change as highest GHG emissions savings require high land use change and minimum land use change causes relatively low GHG emissions savings. There is a relatively weak conflict between NH_3 emissions and land use change criteria. The ideal value for land use change is achieved with a level of NH_3 emissions at around 6% higher than its minimum value while the ideal value for NH_3 emissions is achieved with a level of land use change at around 3% higher than its minimum value.

Table 5.1 Pay-off matrix for the four criteria considered

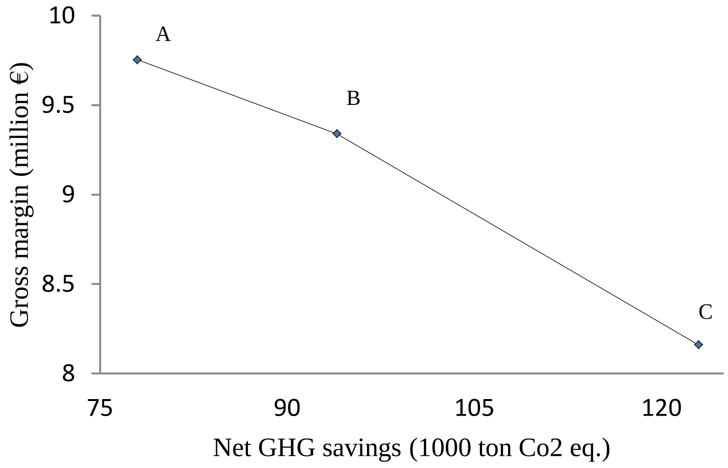
Objective optimized	Gross margin (million €)	GHG emissions (1000 ton CO_2 eq.)	NH3 emissions (ton)	Land use (ha)
Gross margin	9.75	-78	122	1804
GHG emissions	8.16	-123	115	1804
NH_3 emissions	5.87	-105	103	1298
Land use change	6.77	-82	110	1254

Table 5.2 shows the amount of manure processed by each processing technology under optimization of one criterion at a time. For example, when gross margin is maximized, around 14% of the total manure available for processing is allocated to CHP, 26% to green gas and 56% to manure only option to produce a total energy of 1.28 PJ and results in total subsidy of € 17.48 million. When land use change is minimized, 69% of the manure available for processing is allocated to manure only option and 31% to green gas option to produce 1.28 PJ of energy and results in total subsidy of € 14.72 million.

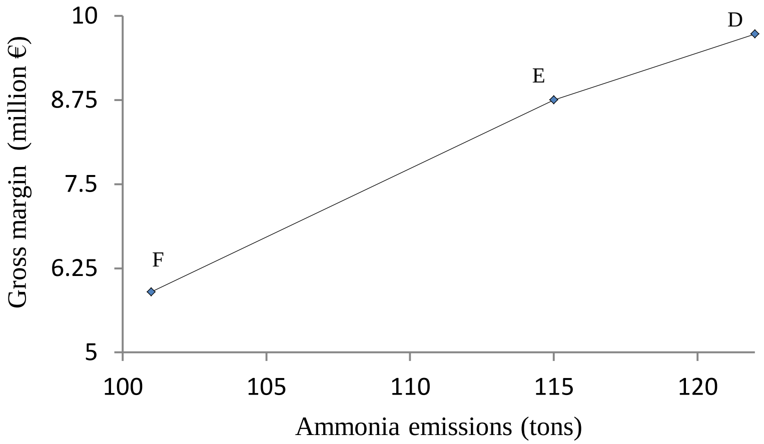
Table 5.2 Manure processed, energy produced and subsidy under different objective optimization

	Objective optimized			
	Gross margin	GHG emission	NH_3 emission	Land use
Manure processed by:				
CHP (ton)	110,460			
Green gas (ton)	160,180	270,640	194,680	188,180
Manure only digestion (ton)	342,860			425,320
Manure separation (ton)		342,860	418,820	
Total energy produced (PJ)	1.28	1.78	1.28	1.28
Total subsidy (million €)	17.48	19.57	14.08	14.72

The pay-off matrix provides useful information to analyse the trade-offs among the four criteria by taking two criteria at a time. Figure 5.2 depicts the trade-off curves of two criteria measuring the relationship between those two criteria. The trade-off curve is obtained by connecting the extreme efficient points. The ideal and anti-ideal points of each criterion form the bounds of the trade-off curves. The slopes of the straight lines connecting the extreme efficient points represent the marginal rate of transformation (shadow prices) between the criteria. For instance, from the trade-off curve between gross margin and GHG emissions savings, the slope of segment AB in figure 5.2 indicates that a 1 ton increase in GHG emissions savings implies a € 25.63 reduction in gross margin while for segment BC the shadow price of GHG in terms of gross margin is € 40.69. Given these sets of points, the decision maker chooses the preferred point. For instance, looking at segment AB, if the decision maker believes that the trade-off is worthwhile then point B is preferred to A; otherwise, point A is preferred to B. The trade-off between gross margin and ammonia emissions indicates that the shadow price of a 1 kg reduction of ammonia emissions in terms of gross margin ranges from € 140 (segment DE) to € 203.57 (segment EF) reduction in gross margin. The transformation curve between gross margin and land use change is linear implying that the shadow price (€ 5409.84) is constant. The trade-off between GHG emissions savings and land use implies that the shadow price of a 1 ha of land in terms of GHG emissions savings is 179 tons (segment GH).

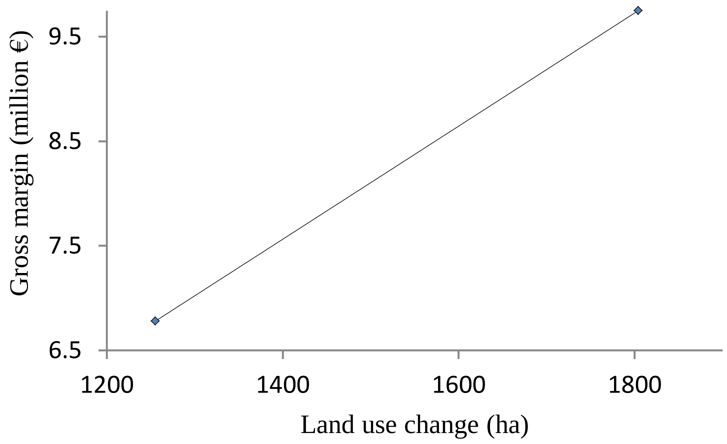


Trade-off curve for Gross margin and GHG savings

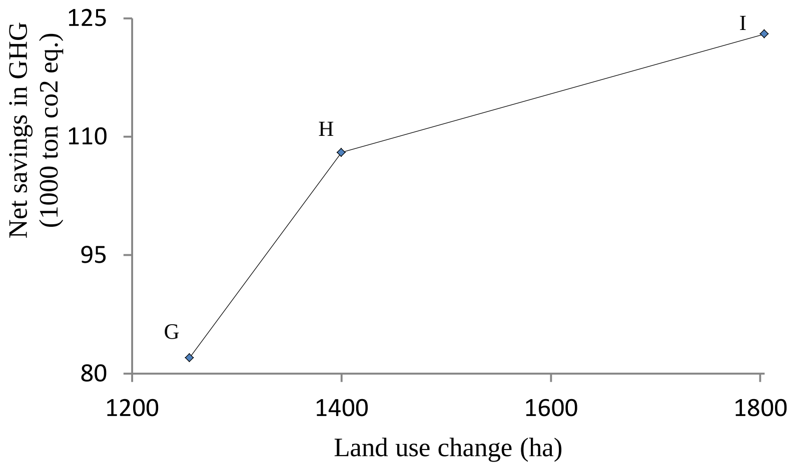


Trade-off curve for Gross margin and Ammonia emissions

Figure 5.2 Trade-off curves



Trade-off curve for Gross margin and Land use change



Trade-off curve for GHG savings and Land use change

(Figure 5.2 Trade-off curves continued)

Optimization of a single criterion gives solutions that are not optimal for all other criteria. Solutions corresponding to maximization of profit are not optimal from an environmental aspect of sustainability and solutions corresponding to minimization of land use change are not optimal from economic and environmental aspects of sustainability. In addition to that, the trade-off curves in Figure 5.2 have a number of efficient points and thus it is important to find a compromise set. The compromise solutions are obtained by resorting to the compromise programming model described in section 5.2.1. Thus, the solutions obtained by taking two criteria at a time in the pay-off matrix are further analysed to find the best compromise using the CP technique.

To show how compromise solutions are obtained, the exercise is performed by taking gross margin and GHG emissions savings criteria. Assuming that the two criteria have equal preference weights, the compromise solutions are shown in the trade-off curve by plotting the solutions for the L_1 and L_∞ metrics as shown in Figure 5.3. These two metrics form the boundary for the compromise set. For this case study, the L_1 and L_∞ solutions are close to each other (almost coinciding) which makes it easier for the decision maker to choose a manure management plan.

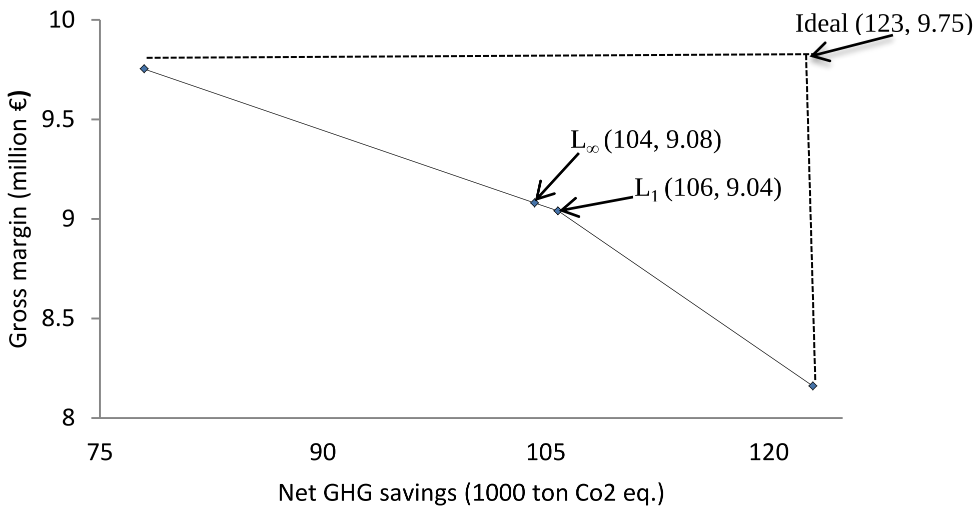


Figure 5.3 Trade-off curve for gross margin and GHG saving and the compromise solutions

5.4.2 Elicitation and aggregation of individual preference weights

In the elicitation of preference weights, first the consistency of the individual PC matrices was checked and then the individual preference weights were computed. PC matrices which were inconsistent were improved by applying model (5.9) described in section 5.2.2. The PC matrices obtained are listed in Appendix 5B. After the individual preference weights were determined, the group weights for each of the criteria were derived.

Table 5.3 shows the individual preference weights obtained from the individual PC matrices before and after modifying the inconsistent PC matrices. It should be noted that only those inconsistent matrices were included in the search for a consistent matrix. Considering the consistency of the matrices, PC matrices of two members of the farmer group (member 2 and 4) and two members of the company group did not satisfy the conditions of consistency at a threshold consistency index of 0.20 according to Saaty's consistency index. Considering the preference weights of the government group, results show that member 1 and 3 give higher importance to reduction of GHG emissions while member 2 gives equal importance to the economic and environmental criteria. For the farmer group, member 1 and 2 give higher importance to land use change while gross margin and GHG emissions are equally important for member 3 and gross margin is more important for member 4. For the academic group, gross margin is more important for member 2 and 3 while member 1 gives equal importance to all criteria. For the company group, both members give higher importance to gross margin.

The weights after improving the PC matrices for which judgements were inconsistent are presented in the second section (improved consistent PC matrix*)* of Table 5.3. For the two members of the farmer group and member 1 of the company group, the weights inferred are close to the weights inferred from the original matrices indicating that the similarity condition is given more weight for these matrices. Considering member 2 of the company group, the weights inferred are not close to the weights inferred from the original matrix indicating that the consistency condition is given more weight than the similarity condition.

Table 5.3 Individual preference weights from original PC matrix and consistent PC matrix

Stakeholder	Criteria			
	Gross margin	GHG emissions	NH3 emissions	Land use change
Original PC matrices:				
Government 1	0.045	0.682	0.136	0.136
Government 2	0.300	0.300	0.300	0.100
Government 3	0.093	0.664	0.111	0.133
Farmer 1	0.303	0.076	0.015	0.606
Farmer 2	0.110	0.022	0.022	0.846
Farmer 3	0.353	0.353	0.118	0.176
Farmer 4	0.703	0.078	0.078	0.141
Academic 1	0.250	0.250	0.250	0.250
Academic 2	0.700	0.100	0.100	0.100
Academic 3	0.608	0.122	0.068	0.203
Company 1	0.738	0.123	0.015	0.123
Company 2	0.700	0.100	0.100	0.100
Improved consistent PC matrix:				
Farmer 2	0.314	0.063	0.063	0.560
Farmer 4	0.703	0.078	0.078	0.141
Company 1	0.667	0.111	0.111	0.111
Company 2	0.427	0.427	0.085	0.061

These individual preference weights were subsequently aggregated by applying the GP model (5.11) in order to obtain the preference weights attached by each social group to each criterion. The group preference weights attached to the four criteria are shown in Table 5.4. The results show that the most important criterion for the government group is reduction of GHG emissions followed by land use change while the farmer group gives higher importance to land use change and gross margin. For the other two social groups, maximizing of profit is the most important criterion.

Table 5.4 Group preference weights

Social group	Criteria			
	Gross margin	GHG emissions	NH_3 emissions	Land use change
Government	0.093	0.664	0.136	0.107
Farmer	0.314	0.076	0.063	0.547
Academic	0.608	0.100	0.089	0.203
Company	0.667	0.111	0.111	0.111

5.4.3 Results of compromise programming model

As shown in the trade-off analysis, the ideal solutions cannot be achieved for all criteria simultaneously. Hence we resort to a geometric measure of distance to find a feasible compromise solution that has a minimum deviation from the ideal vector. Applying the CP model described in section 5.2.1 and assuming that all criteria have equal preference weights, the compromise solutions for L_1 and L_∞ metrics are shown in Table 5.5. These solutions represent the range of efficient manure management plans that are best compromise solutions.

The compromise solution for L_1 shows that land use change and NH_3 emissions are close to their ideal values whereas the gross margin and GHG emissions are far away from their ideal values. Gross margin achieved 40% less than its ideal and GHG emissions achieved 15% less than its ideal value. Thus, this option is characterized by low gross margin and low GHG emissions savings with reduced land use change and ammonia emissions. The values of the decision variables corresponding to the compromise solution for L_1 metric show that around 68% of the total manure is processed by manure-only option and the remaining 32% by green-gas option to produce a total energy of 1.28 PJ.

Table 5.5 Results of the compromise programming model

	L_1	L_∞	Ideal value
Criteria:			
Gross margin (million €)	5.87	7.49	9.75
GHG emissions (1000 ton)	-105	-100	-123
NH3 emissions (ton)	103	110	103
Land use change (ha)	1298	1575	1254
Manure processed (ton):			
CHP		57,000	
Green gas	195,000	180,000	
Manure only digestion	419,000		
Manure separation		377,000	
Total energy produced (PJ)	1.28	1.55	
Total subsidy (million €)	14.08	15.56	

The compromise solution for L_∞ generates a more balanced achievement of the criteria compared to the L_1 solution. Under this option, the achievement of the ideal value has improved by 17% for gross margin. For land use change, the L_∞ solution is worsened by 26% compared to its ideal value. The achievement of NH_3 emissions is 7% below its ideal value implying that economic performance can be improved without significantly increasing the NH_3 emissions. Thus, as $P \rightarrow \infty$, the solution trades off NH_3 emissions and land use change for gross margin. This option is characterized by improved gross margin with higher land use change. The values of the decision variables corresponding to the L_∞ solution show that around 40% of the total manure is allocated to CHP and green-gas option and 60% to manure-separation option.

The L_1 solution represents the compromise that minimizes the maximum disagreement. This solution is biased towards land use change and ammonia emissions. The L_∞ solution represents the most balanced solution between achievements of the criteria considered where gross margin, GHG emissions, NH_3 emissions and land use change achieve 77%, 81%, 93% and 79% of their ideal values, respectively. Therefore, if land use change is the pressing issue, then the decision maker chooses the L_1 solution where it achieves 97% of its ideal value. If the decision maker is looking for a solution that achieves the best equilibrium among the different criteria, then the L_∞ solution is chosen.

The preference weights attached to each of the criteria were finally introduced into the compromise model. Table 5.6 presents the results of the CP model assuming the different social groups' weights. The model was solved for each of the three social groups' vector of weights and thus creating three scenarios. The first scenario corresponds to the case of provincial government decision maker, the second scenario to the farmer decision maker and the third scenario to company decision maker. The corresponding results for both metrics are shown.

Table 5.6 Compromise solutions for the three decision makers' preferential weights (W_i^*)

	Government		Farmer		Company	
Criteria	L_1	L_∞	L_1	L_∞	L_1	L_∞
Gross margin (million €)	9.04	7.43	6.76	7.69	9.75	7.88
GHG emissions (1000 ton)	-105	-117	-82	-102	-78	-97
NH3 emissions (ton)	122	113	110	107	122	115
Land use change (ha)	1804	1643	1254	1482	1804	1804

$^*W_i$ = (Gross margin, GHG emissions, NH_3 emissions, Land use change)
Government W_i = (0.09, 0.66, 0.14, 0.11); Farmer W_i = (0.31, 0.08, 0.06, 0.55); Company W_i = (0.67, 0.11, 0.11, 0.11)

Under government group weights scenario, the compromise solution for L_1 shows that gross margin achieved 93% of its ideal value, GHG emissions achieved 85% , NH_3

emissions achieved 83% whereas land use change achieved only 56% of its ideal value. The compromise solution for L_∞ under government group weight scenario shows that GHG emission is close to its ideal value whereas gross margin is 24% below its ideal value. Thus, as $P \rightarrow \infty$, the solution trades off gross margin for GHG emissions savings. Under farmer group weights scenario, the solution for L_1 shows that land use change and NH_3 emissions are close to their ideal values whereas gross margin and GHG emissions are respectively 31% and 33% below their ideal values. The solution for L_∞ under farmer group weight scenario shows an improvement in the achievement of gross margin and GHG emissions savings. Under company group weights scenario, the solution for L_1 shows that only gross margin is close to its ideal value. The solution for L_∞ shows that all the criteria are far away from their ideal values. Therefore, depending on which decision maker group weights are assumed, a variety of best compromise manure management plans are generated.

5.5 Discussion and conclusions

This chapter analysed the trade-offs between economic, social and environmental sustainability of various manure processing systems at the regional level and integrated the views of different decision makers. The study focused on manure management in the animal dense region Salland.

Four criteria were used to analyse trade-offs between different sustainability criteria i.e. gross margin, greenhouse gas (GHG) emissions, ammonia (NH_3) emissions and land use change. These criteria were subsequently evaluated by four decision maker groups namely, provincial government, farmers, dairy processing company and academic group. The trade-offs between the different criteria were analysed using a multi-objective programming (MOP) and generating payoff matrix. Decision maker group preference weights were elicited and aggregated using analytical hierarchy process (AHP) and goal programming (GP). Best compromise manure management plans were generated using a compromise programming (CP). Results from the MOP showed that there is a conflict between the different criteria. This conflict occurs between gross margin and the other three criteria i.e. highest gross margin requires high emissions of NH_3, high land use change and low GHG emissions savings. The shadow price of a 1 ton GHG emissions savings in terms of gross margin is € 25.63, of a 1 kg reduction in NH_3 emissions it is € 140 and of a 1 ha reduction in land use it is € 5409.84. The shadow prices are useful in assisting decision makers to make trade-offs in a transparent manner, i.e. the shadow prices enable decision makers to explicitly determine if trade-offs between the different criteria are worthwhile. Results further showed that there is a conflict between GHG emissions savings and land use change as the highest GHG emissions savings require high land use change and the minimum land use change causes relatively low GHG emissions savings. Results from aggregation of preference weights of decision makers showed that decision makers in manure management have different and conflicting interest. The most important criterion for the provincial government is reduction of GHG emissions, for farmers it is reduction of land use change, for dairy processing company and for academic group, it is maximization of gross margin. Assuming that all criteria have equal preference weights, the CP generated the compromise solutions for L_1 and L_∞ metrics. Results from CP showed that the L_1 solution is biased towards NH_3 emissions and land use change, i.e. both NH_3 emissions and land use change are close to their ideal values whereas gross margin and GHG emissions are far away from their ideal values. The L_∞ solution showed the best equilibrium among the different criteria, i.e. gross margin achieved 77% of its ideal value, GHG emissions achieved 81%, NH_3 emissions achieved 93% and land use change achieved 79% of its ideal value. In conclusion, best compromise solutions assuming equal preference weights of all criteria indicated that manure processing in Salland results in GHG emission savings ranging from 100 kiloton CO_2 eq. to 105 kiloton CO_2 eq. and require 1298 ha to 1575 ha of land. This suggests that manure processing in Salland achieves about 5% of the target CO_2 emissions reduction of the province of Overijssel.

The environmental data are average emissions reported by life cycle assessment (LCA) studies (Zwart K, 2006; Van der Voet et al., 2008; De Vries et al., 2010). GHG and NH_3 emissions vary due to variations in composition of co-substrates used and efficiency of the manure processing technology (De Vries et al., 2010). Nevertheless, the study used emission data reported by LCA studies which are compatible with the Dutch conditions.

The preference weights attached to each of the criteria were elicited from a small number of different groups of decision makers and the question is whether the elicited preference weights represent the views of the broader group. One of the advantages of the analytical hierarchy process (AHP) is that it is not necessary to involve a large sample. This method also gives an insight into the consistency of the judgment of decision makers. Several authors conducted AHP surveys with a small sample size ranging from 9 to 23 stakeholders (Linares and Romero, 2002; Marchamalo and Romero, 2007; Diaz-Balteiro et al., 2009; Nordstorm et al., 2009). In our study the farmer group was selected randomly and the opinion of these farmers is not representative of farmers in the Netherlands.

Presumably, there are differences in perceptions of farmers about the different sustainability criteria depending on their demographic and socio-economic characteristics. Conducting surveys among farmers that capture differences in demographic and socio-economic characteristics and clustering those farmers with similar characteristics into groups would give a more representative view of farmers. The elicited preference weights of the provincial government and dairy processing company are representative for the province of Overijssel and for the dairy processing company respectively whereas the preference weights of the academic group are not representative.

The methodology applied in this study can be used as a tool to assist decision makers and policy makers in designing policies that enhance the introduction of economically, socially and environmentally sustainable manure management systems. Quantifying trade-offs gives an insight into the conflicts and trade-offs among the different sustainability criteria and thus support decision-making. The best compromise solution, compared to the solutions obtained when each criterion is optimized separately, provides an alternative solution that strikes a balance among all the criteria considered. This enhances the decision maker's understanding of how such best compromise solution balances the different sustainability criteria. The methodology proposed in this study can be applied to address manure management problems in different regions. It provides a diversity of sustainable solutions for different situations and is flexible as to adapt to local conditions and future changes.

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Appendix 5A. Data

Table 5A.1 Economic data of manure processing technologies

	Unit	CHP[1]	GG[1]	MO[2]	MS[3]
Technical data:					
Energy yield	MJ/ton	978.46	3287.48	140.94	n.a.[4]
Digestate	ton/ton	0.8	0.8	0.8	0.75
Economic data:					
Feed-in tariff	€/MJ	0.042	0.015	0.042	n.a.
Investment cost	€/MJ or €/ton	0.0146	0.0015	0.0635	6.88[5]
O & M cost	€/MJ or €/ton	0.0046	0.0046	0.006	10.03[5]
Biomass cost	€/MJ	0.012	0.0042	0	0
Fixed cost	€/MJ or €/ton	0.0023	0.0003	0.0023	1.83[5]
Digestate cost	€/ton	5	5		

CHP= Combined heat and power unit, GG= Green gas, MO = Manure only digestion, MS= Manure separation

[1]Gebrezgabher et al., 2012; [2]Kool et al., 2005; [3]Melse and Verdoes, 2005; [4]n.a.= not applicable; [5]€/ton

Table 5A.2 Environmental data: GHG and NH_3 emissions during processing

	Emission	unit	Digestion	Source
Manure :				
Storage	N_2O	kg/ton	0.0006	Zwart and Kuikman, 2011
	CH_4	kg/ton	0.2325	Zwart and Kuikman, 2011
Maize:				
Fertilization	N_20	kg/ton	0.27	Zwart and Kuikman, 2011
Crop production	CO_2	kg/ton	30	Zwart and Kuikman, 2011
	NH_3	Kg/ton	17	Zwart et al., 2006
Transport	CO_2	kg /ton	0.876	Zwart and Kuikman, 2011
Storage	N_2O	kg/ton	0.00035	Zwart and Kuikman, 2011
	CH_4	kg/ton	0.16	Zwart and Kuikman, 2011
Other co-digestion:				
Grass: CO_2	CO_2	kg/ton	82.7	Van der Voet et al., 2008;
Grass: CH_4	CH_4	kg/ton	0.147	Van der Voet et al., 2008;
Grass: N_2O	N_2O	kg/ton	0.404	Van der Voet et al., 2008;
Other co-product	CO_2	kg/ton	0.876	Zwart and Kuikman, 2011
Digestate:				
Storage	CH_4	kg/ton	1	Kool et al., 2005; Amon et al., 2006
	N_2O	kg/ton	0.04	Kool et al., 2005; Amon et al., 2006
Transport	CO_2	kg/ton	1.314	Kool et al., 2005; Amon et al., 2006
Application	CH_4	kg/ton	0.002	Amon et al., 2006
	N_2O	kg/ton	0.0027	Amon et al., 2006
	NH_3	kg/ton	0.22	Amon et al., 2006

Table 5A.3 Other assumptions on conversion units and maize yield

Item	Unit	Value
Conversion of electricity to MJ	MJ/kwh	3.6
Conversion of green gas to MJ	MJ/m^3	39.8
CO_2 emission factor primary energy-electricity	kg CO_2/MJ	0.069
CO_2 emission factor primary energy-natural gas	kg CO_2/MJ	0.056
Global warming potential:		
CO_2	kg CO_2/kg	1
CH_4	kg CO_2/kg	21
N_2O	kg CO_2/kg	310
Yield maize	ton/ha	45

Appendix 5B. Pairwise comparison matrices of each member of the social group

Government 1

$$\begin{array}{c c} & \begin{array}{cccc} \text{Profit} & \text{GHG} & \text{NH3} & \text{Land} \end{array} \\ \begin{array}{c} \text{Profit} \\ \text{GHG} \\ \text{NH3} \\ \text{Land} \end{array} & \begin{bmatrix} 1 & 0.20 & 0.33 & 0.33 \\ 5 & 1 & 5 & 5 \\ 3 & 0.20 & 1 & 3 \\ 3 & 0.20 & 0.33 & 1 \end{bmatrix} \end{array}$$

Government 2

$$\begin{array}{c} \begin{array}{cccc} \text{Profit} & \text{GHG} & \text{NH3} & \text{Land} \end{array} \\ \begin{bmatrix} 1 & 1 & 1 & 3 \\ 1 & 1 & 0.25 & 3 \\ 1 & 4 & 1 & 5 \\ 0.33 & 0.33 & 0.20 & 1 \end{bmatrix} \end{array}$$

Government 3

$$\begin{array}{c} \begin{array}{cccc} \text{Profit} & \text{GHG} & \text{NH3} & \text{Land} \end{array} \\ \begin{bmatrix} 1 & 0.14 & 4 & 0.25 \\ 7 & 1 & 6 & 5 \\ 0.25 & 0.17 & 1 & 0.25 \\ 4 & 0.20 & 4 & 1 \end{bmatrix} \end{array}$$

Farmer 1

$$\begin{array}{c c} \begin{array}{c} \text{Profit} \\ \text{GHG} \\ \text{NH3} \\ \text{Land} \end{array} & \begin{bmatrix} 1 & 4 & 4 & 0.50 \\ 0.25 & 1 & 5 & 0.17 \\ 0.25 & 0.20 & 1 & 0.11 \\ 2 & 6 & 9 & 1 \end{bmatrix} \end{array}$$

Farmer 2

$$\begin{bmatrix} 1 & 5 & 5 & 0.13 \\ 0.20 & 1 & 0.25 & 0.20 \\ 0.20 & 4 & 1 & 0.20 \\ 8 & 5 & 5 & 1 \end{bmatrix}$$

Farmer 3

$$\begin{bmatrix} 1 & 2 & 3 & 0.50 \\ 0.50 & 1 & 3 & 2 \\ 0.33 & 0.33 & 1 & 0.50 \\ 2 & 1 & 2 & 1 \end{bmatrix}$$

Farmer 4

$$\begin{array}{c c} \begin{array}{c} \text{Profit} \\ \text{GHG} \\ \text{NH3} \\ \text{Land} \end{array} & \begin{bmatrix} 1 & 9 & 9 & 5 \\ 0.11 & 1 & 0.33 & 5 \\ 0.11 & 3 & 1 & 0.20 \\ 0.20 & 0.20 & 5 & 1 \end{bmatrix} \end{array}$$

Academic 1

$$\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix}$$

Academic 2

$$\begin{bmatrix} 1 & 7 & 7 & 7 \\ 0.14 & 1 & 0.14 & 1 \\ 0.14 & 7 & 1 & 7 \\ 0.14 & 1 & 0.14 & 1 \end{bmatrix}$$

Academic 3

$$\begin{array}{c c} \begin{array}{c} \text{Profit} \\ \text{GHG} \\ \text{NH3} \\ \text{Land} \end{array} & \begin{bmatrix} 1 & 5 & 9 & 3 \\ 0.20 & 1 & 9 & 3 \\ 0.11 & 0.11 & 1 & 0.11 \\ 0.33 & 0.33 & 9 & 1 \end{bmatrix} \end{array}$$

Company 1

$$\begin{bmatrix} 1 & 6 & 6 & 6 \\ 0.17 & 1 & 8 & 0.25 \\ 0.17 & 0.13 & 1 & 0.17 \\ 0.17 & 4 & 6 & 1 \end{bmatrix}$$

Company 2

$$\begin{bmatrix} 1 & 7 & 7 & 7 \\ 0.14 & 1 & 5 & 7 \\ 0.14 & 0.20 & 1 & 6 \\ 0.14 & 0.14 & 0.17 & 1 \end{bmatrix}$$

Chapter 6

General Discussion

6.1 Introduction

The general objective of this thesis was to assess the economic, social and environmental sustainability of manure processing and to develop a decision-making tool to assist decision makers in designing sustainable manure management systems. This general objective was broken down into four specific objectives that were dealt with in separate chapters. Manure processing technologies considered in this research were anaerobic digestion and manure separation. Chapter 2 analysed the factors influencing a farmer's strategy to adopt a manure separation technology. In this chapter, a conceptual and empirical framework for the analysis of the factors explaining the likelihood of adoption of the technology was developed. Chapter 3 analysed the economic performance of anaerobic digestion of manure with a combined heat and power (CHP) unit under different policy scenarios. In Chapter 4, the economic analysis was extended to incorporate the uncertainties associated with technical and economic parameters of anaerobic digestion of manure with upgrading of biogas (green gas). The overall sustainability assessment of manure processing is presented in Chapter 5. In this chapter trade-offs between sustainability criteria are analysed using a multi-criteria decision making (MCDM) method.

This concluding chapter presents and discusses the main findings of this research as well as their policy and business implications. This chapter proceeds as follows. The second section of this chapter discusses methodological choices and data used. The third section presents main findings and their policy and business implications. The fourth section provides suggestions for future research and the last section presents the main conclusions of the thesis.

6.2 Methodological and data issues

A variety of methods and data sources were used to achieve the specific objectives of this thesis. This section presents a brief discussion on the methodological choices made and on the data used in achieving the specific objectives.

Modelling issues

In order to analyse the economic, social and environmental sustainability of manure processing and to determine the decision-making behaviour of farmers who are potential adopters of manure processing technologies, econometric (Chapter 2), mathematical (Chapter 3 and 5) and simulation (Chapter 4) models were applied in this research. In Chapter 2 a multistep approach was used, which integrated multivariate data analysis with an ordered response model to estimate the likelihood of adoption of manure separation technology. The methodological approach used in this chapter has the advantage that; 1) it included attitude variables in the explanatory model of behaviour; 2) it tested the hypothesis that attitude variables are determined by demographic and socio-economic variables; 3) it solved the problem of endogeneity; and 4) it predicted the likelihood of adoption. The study uses farmers' intended adoption. While the stated adoption is not a completely accurate predictor of actual adoption, it still provides insights in future plans of farmers regarding the adoption of the technology.

Mathematical programming and stochastic simulation models were applied in this research to analyse the economic (Chapter 3 and 4) and to assess overall sustainability (Chapter 5) of manure processing technologies. The economic aspect of anaerobic digestion of manure was analysed using a linear programming (LP) model in Chapter 3 which was subsequently extended to include environmental and social aspects of sustainability in Chapter 5. The risk analysis that was modeled in a stochastic simulation model was also a follow-up of the economic analysis in Chapter 3, but it addressed the issue of uncertainties associated with technical and economic parameters of anaerobic digestion.

An LP model was used in Chapter 3 to analyse the economic performance of anaerobic digestion of manure. The advantage of using an LP model is that it allowed for a detailed analysis of different policy scenarios. However, the LP model in Chapter 3 takes only one aspect, i.e. economic performance and hence gives only partial insight. Moreover, the model had a drawback in that it failed to incorporate uncertainties associated with estimating technical and economic parameters of anaerobic digestion. In Chapter 4, a stochastic simulation model was used to address uncertainties associated with technical and economic parameters of anaerobic digestion.

Chapter 5 used multi-criteria decision making (MCDM) to model economic, environmental and social aspects of manure processing and to integrate the views of different decision makers. There are several MCDM methods and the choice of which MCDM method to use depends on the type of information that is available and the number of criteria considered. In this research, the choice of the MCDM methods is justified based on the fact that the manure problem being modelled involves few criteria. In addition to that, the fact that we do not have information about the decision maker's specific target for each of the selected criteria makes both multi-objective programming (MOP) and compromise programming (CP) more appropriate compared to other MCDM methods (Romero and Rehman, 2003).

Selection of indicators

In sustainability assessment, the selection of sustainability indicators is an important step (Balkema et al., 2002). In Chapter 5, four indicators were used to assess sustainability of manure processing namely gross margin, greenhouse gas (GHG) emissions, ammonia (NH_3) emissions and land use change. To measure economic sustainability, other indicators such as net present value which take a long term perspective are also used. Gross margin was selected as it is easily understood by decision makers. To measure environmental sustainability, a wide range of impacts such as eutrophication and acidification potential are used (De Vries et al., 2010; Van Calker et al., 2004). In this research, to analyze the trade-offs between different environmental indicators, GHG and NH_3 emissions were selected. Land use change was interpreted as a social aspect related to manure processing. This criterion measures the land required for the production of co-substrate mainly silage maize used in the digestion process. However, it does not include indirect land use changes caused by the fact that this land will not be available for the production of food or feed. For the social aspect of sustainability, other studies included local prosperity or job creation as indicators (Balkema et al., 2002). However, the contribution of manure processing to local prosperity and the creation of jobs in the local community is considered negligible as most processing installations are built on an existing livestock farm.

Data used

Different data sources were used in this research. Data from the agricultural census and survey data collected from 350 dairy farmers were used for analyzing the manure separation technology adoption decision (Chapter 2). Furthermore, empirical data of 24 biogas plants in combination with expert data were used to analyse the technical and economic performance of anaerobic digestion with CHP and green gas units (Chapter 3, 4 and 5).

The sample for the survey in Chapter 2 consisted of those farms that are part of the Dutch Farm Accountancy Data Network (FADN) which made it possible to link the survey data with the demographic and socio-economic data from the agricultural census. However, more variables could have been included to strengthen the analysis. Since the analysis was based on survey data of dairy farmers only, it was unable to capture differences between different types of livestock farms. The analysis in this study could be improved by including pig farmers and arable farmers in the survey. Including pig farmers would reveal if the type of livestock farm is an important determinant of adoption in the future. Conducting a survey among arable farmers could give an insight into the arable farmers' willingness to pay for the manure products. In addition to that, including data on the financial position of the farm would strengthen subsequent analysis.

One of the major problems in economic analysis of manure processing in the Netherlands is the lack of data. The operating biogas plant used as a case study in Chapter 3 was in a starting-up phase and reliable estimates of technical performance could not be obtained. The analysis had to be based on a number of assumptions including the biogas yield which was based on parameters from literature. The data from the 23 biogas plants in Chapter 4 is a cross section data and does not provide variation over time of the technical and economic performance of a given plant. In addition to that, the biogas plants use an array of different feedstocks as co-substrates which makes it more difficult to get an accurate technical performance.

In addition to objective data, expert or stakeholder elicitation was used in this research. A number of experts were consulted to identify relevant business models and to specify the mean and range of values (lower or upper limit) of model parameters (Chapter 4). Moreover, experts and decision makers were consulted to elicit preference weights given to the different sustainability criteria (Chapter 5). Experts are from the Dutch Ministry of Economic Affairs, Agriculture and Innovation (EL&I), Senternovem, a dairy processing company, the experimental biogas plant "De Marke" and a provincial government who are involved in decision-making or studies related to manure processing. Dairy farmers were also included in eliciting preference weights given to the different sustainability criteria. The data from experts are subjective but provided useful insights into the existing business and policy issues related to manure processing from different perspectives.

6.3 Implications of the study

Business implications

The empirical model in Chapter 2 analysed the likelihood of adoption of manure separation technology to mitigate environmental hazards emanating from livestock production. The results of this study are useful for technology developers and distributors in identifying what determines the decision-making behaviour of farmers and to identify and target those farmers who will most likely adopt the technology in the future.

For a potential investor, making an optimal investment decision in manure processing is a challenge due to the uncertainties about the performance of these technologies. Important implications of the results from the economic analyses of manure digestion (Chapter 3 and 4) are that manure digestion is not profitable without subsidies and that the economic performance improves, if the digestate is treated as a replacement of artificial fertilizer. Investment in anaerobic digestion with green gas is on average more profitable than anaerobic digestion with CHP unit. The LP model developed in Chapter 3 could be used by biogas plants, especially large plants, as a decision-making tool to assist in managing the large amount of digestate. The simulation model developed in Chapter 4 is suitable for evaluating investment decisions in anaerobic digestion as it provides useful information about the risks and profitability of such investments.

Policy implications

To our knowledge there were less than 90 farm-scale biogas plants and 8 pilot manure separation installations in the Netherlands in the year 2010 (Hjort-Gregersen et al., 2011). Economic policies of manure management present conditions which determine if a given technology is attractive to potential adopters such as farmers (Petersen et al., 2007). Manure processing technologies are needed to control nutrient surpluses and to mitigate the environmental impacts. However, the development of manure processing is impeded by the uncertainty in government subsidy and by the lack of well-defined market conditions for manure products. This study provides useful policy implications. First, attitudes of farmers toward the technology (manure separation) were analysed. This assists policy makers in identifying and targeting potential adopters of manure separation. Second, the uncertainties faced by potential investors were identified (investment cost, biogas yield, price of co-substrates, digestate disposal). Results help in designing policy instruments for reducing these uncertainties.

The MCDM model developed in Chapter 5 can be used to manage manure problems at the regional scale. Quantifying the trade-offs between economic, social and environmental aspects enables policy makers to grasp the inherent conflicts and trade-offs among the different sustainability criteria and thus supports decision-making. Since the size of the manure problem differs by region, it is expected that different regions have different priorities and thus call for different strategies to mitigate manure related problems. The proposed methodology is flexible as to adapt to the needs and priorities of different regions. The method is a useful tool in assisting policy makers in designing policies that enhance the introduction of socially, economically and environmentally sustainable manure management systems. The method can also be used for other waste management problems such as municipal solid waste management.

6.4 Future outlook

The societal concerns about sustainability of livestock production systems combined with the tightening of environmental requirements to mitigate manure related problems may trigger technological innovations that offer opportunities for the agricultural sector. Consequently, a farmer seeking to comply with these obligations in the most cost-effective way faces a pallet of technology options. Making an optimal investment decision is a challenge due to uncertainties about the performance of the processing technologies and due to institutional uncertainties. Dutch renewables policy has been widely criticized for being too unstable to provide sufficient incentives for investments in renewable energy technologies and due to the complicated permit regulations (Van Rooijen and Van Wees, 2006). Therefore, given the variety of uncertainties that farmers face, the option to postpone an adoption decision has a value for the farmer (Purvis et al., 1995). The *ex ante* approach to technology adoption and the risk analysis conducted in this research could be used as a basis for extending the analysis into an option pricing method. Applying option pricing methods into manure processing technology adoption under uncertainty is relevant as farmers rarely face a dichotomous choice, i.e. to invest or not. Rather they may choose among options such as to either invest now or postpone the decision (Dixit and Pindyck, 1994; Purvis et al., 1995).

Starting from the mid 1980s, a policy aim of the Dutch government has been to reach a balanced manure market, implying that manure production capacity should be equal to manure application capacity (Vrolijk et al., 2008). Empirical research analysing the impact of manure processing on the overall manure market and on the extent to which processing technologies contribute to achieving a spatial equilibrium in the manure market is yet another interesting topic for future research. To analyse the manure market, the Agricultural Economics Research Institute (LEI) has developed a micro-simulation model called MAMBO which is a model of livestock and agriculture that looks at the mineral flows within the sector and the resulting emissions (Vrolijk et al., 2008). The current version of MAMBO models the mineral flows and the resulting emissions from unprocessed manure. The model can be extended to include the impacts of manure processing on the overall manure market. This can be done by linking the analysis of the likelihood of adoption and the technical performance of manure processing with MAMBO model.

Finally, the analysis in this research focused on manure management which is one aspect of overall farm management. However, the type of manure processing applied must be compatible with the existing farming system. Manure management decisions must also take into consideration livestock and crop production and marketing plans of the farm (Stonehouse et al., 2002). The MCDM method applied in this research can also be applied to develop a decision support tool to assess the technical, economic, social and environmental sustainability of manure management in the context of a whole farm planning. Whereas, at farm level, there is one decision maker, the multi-criteria approach can be applied to assist the farm decision maker in designing a sustainable whole farm plan.

6.5 Main conclusions

The following main conclusions are drawn from this thesis:

- In addition to socio-economic and demographic characteristics, a dairy farmer's attitude towards the different attributes of manure separation technology are important determinants of a farmer's strategy to adopt the technology. Attributes include perceived attractiveness of manure products, ability to use nitrogen and phosphate optimally and the perceived environmental benefit from adopting the technology. Overall, 51% of the dairy farmers do not consider manure separation as a future strategy.

- Under current legislation which regards the reverse osmosis concentrate as animal manure and with the currently low values of digestate and heat, investments in anaerobic digestion technologies with combined heat and power (CHP) units are not profitable without subsidies.
- Despite current levels of subsidies provided to green gas production from anaerobic digestion of manure, there is a probability of a negative net present value (NPV), i.e. accounting for uncertainties in technical and economic parameters suggests a probability of a negative NPV of 46% for a stand-alone plant and of 42% for a central upgrading.
- In manure management, it is difficult to optimize economic, social and environmental objectives simultaneously. Conflicting objectives occur between GHG emissions savings and land use change, i.e. the highest GHG emissions savings require high land use change and minimum land use change causes relatively low GHG emissions savings.
- Decision makers in manure management have different and conflicting interests. The most important criterion for the provincial government is reduction of GHG emissions, for farmers it is reduction of land use change and for the dairy processing company, it is maximization of gross margin.

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Summary

The intensification of livestock operations in the past decades has resulted in an increased concern on the environmental impacts of livestock operations. Environmental impacts include discharges of nitrogen, phosphate and heavy metals to soils and surface waters as well as emissions into the atmosphere. Poor manure management is often the basis of these problems. This has prompted governments, livestock farmers and other stakeholders to explore alternative manure handling and utilization methods such as manure processing technologies. The objective of this thesis is to assess the economic, social and environmental sustainability of manure processing and to develop a decision-making tool to assist decision makers in designing sustainable manure management systems in the Netherlands. Manure processing technologies considered in this study are anaerobic digestion and manure separation.

While there is a growing interest in manure processing technologies, the adoption of such technologies is not successful in the Netherlands. Chapter 2 analysed the factors influencing dairy farmer's likelihood of adoption of manure separation technology by including attitude variables, in addition to demographic and socio-economic characteristics in an explanatory model of behaviour. The empirical results show that a farmer's attitude towards the technology is explained by the demographic and socio-economic characteristics such as the age and level of education of the farmer and the type of manure application technique used in the farm. Farmers' attitudes towards the different attributes of manure separation technology have a significant impact on the likelihood of adoption. Attributes include perceived attractiveness of manure products, ability to use nitrogen and phosphate optimally and the perceived environmental benefit from adopting the technology. Moreover, results show that 51% of dairy farmers do not consider manure separation as a future strategy. Although the technology is well developed and provides an alternative means to mitigate the environmental hazards emanating from animal production, the attitudes of farmers towards the technology are important factors affecting technology adoption.

One of the considerations in deciding upon investment in anaerobic digestion is its profitability. In addition to biogas, anaerobic digestion produces digestate, which consists of a mixture of liquid and solid fractions. A reliable and generally accepted means of disposing of the digestate is of crucial importance for the economic and environmental viability of a biogas plant. In Chapter 3, a linear programming (LP) model is used to analyse the economic performance of anaerobic digestion at farm level under two policy

scenarios. The first scenario focuses on the application of digestate as green fertilizer, i.e. as replacement of artificial fertilizer and the second scenario focuses on the government subsidy for green energy production. The Green Power biogas plant which is a relatively large plant with an installation capacity of 70,000 tons of input on an annual basis formed the basis for this analysis. The plant produces electricity, heat in a combined heat and power (CHP) unit and three types of digestates, namely fixed fraction (FF), ultra filtration (UF) and reverse osmosis (RO). Currently the RO concentrate is treated as animal manure. Results show that when the RO concentrate is treated as a green fertilizer, it is transported to farms close to the biogas plant thus resulting in lower transportation costs and less environmental impact. Therefore, treating RO as a green fertilizer is not only profitable for the plant but it also lessens the environmental burden of long distance transportation of concentrates. Considering subsidies, results show that manure digestion with a CHP unit is not profitable without subsidies.

Chapter 4 analysed the impact of uncertainties associated with technical and economic parameters on the performance of anaerobic digestion of manure with upgrading of biogas (green gas). The analysis is based on the dairy sector's initiative (energy-neutral dairy chain) to produce and utilize green energy. A stochastic simulation model of producing 17 PJ of energy from two business models namely stand-alone green gas and central upgrading is developed. The two business models upgrade biogas into green gas but differ in their organization. In the stand-alone plant, production and upgrading of biogas is done in one plant while in central upgrading, two biogas plants deliver biogas to a central upgrading unit. Simulation results show that the probability that the business models result in a negative net present value (NPV) is 46% for the stand-alone green gas plant and 42% for the central upgrading plant.

The economic analyses of manure processing in the previous chapters are extended to include environmental and social aspects of sustainability in Chapter 5. Multi-criteria decision making (MCDM) methods such as multi-objective programming (MOP), compromise programming (CP) and goal programming (GP) are used to analyse trade-offs between economic, social and environmental criteria while taking decision makers' views of the different criteria into account. Four criteria are used to analyse trade-offs between different sustainability criteria, i.e. gross margin, greenhouse gas (GHG) emissions, ammonia (NH_3) emissions and land use change. These criteria are subsequently evaluated by four decision maker groups namely, provincial government, farmers, dairy processing company and academic group. Manure management in the animal dense region Salland is used as a case study. Results show that there is a conflict between gross margin and the other three criteria, i.e. the highest gross margin requires high emissions of NH_3, high land use change and low GHG emissions savings. Moreover, the highest GHG emissions savings require high land use change and the minimum land use change causes relatively low GHG emissions savings. Results from aggregation of preference weights of decision makers showed that decision makers in manure management have different and conflicting interest. The most important criterion for the provincial government is reduction of GHG emissions, for farmers it is reduction of land use change, for dairy processing company and for academic group, it is maximization of gross margin. These trade-offs among the criteria suggest the need to look for best compromise solutions among the criteria in order to design sustainable manure management systems.

Finally, Chapter 6 gives a synthesis of the methodologies and data used in the previous chapters and discusses briefly the main findings as well as their policy and business implications. The main conclusions of this thesis are summarized as follows:

- In addition to socio-economic and demographic characteristics, a dairy farmer’s attitude towards the different attributes of manure separation technology are important determinants of a farmer’s strategy to adopt the technology. Attributes include perceived attractiveness of manure products, ability to use nitrogen and phosphate optimally and the perceived environmental benefit from adopting the technology. Overall, 51% of the dairy farmers do not consider manure separation as a future strategy.
- Under current legislation which regards the reverse osmosis concentrate as animal manure and with the currently low values of digestate and heat, investments in anaerobic digestion technologies with combined heat and power (CHP) units are not profitable without subsidies.
- Despite current levels of subsidies provided to green gas production from anaerobic digestion of manure, there is a probability of a negative net present value (NPV), i.e. accounting for uncertainties in technical and economic parameters suggests a probability of a negative NPV of 46% for a stand-alone plant and of 42% for a central upgrading.
- In manure management, it is difficult to optimize economic, social and environmental objectives simultaneously. Conflicting objectives occur between GHG emissions savings and land use change, i.e. the highest GHG emissions savings require high land use change and minimum land use change causes relatively low GHG emissions savings.

- Decision makers in manure management have different and conflicting interests. The most important criterion for the provincial government is reduction of GHG emissions, for farmers it is reduction of land use change and for the dairy processing company, it is maximization of gross margin.

Samenvatting

De intensivering van de veehouderij leidt onder meer tot toenemende zorgen rond het milieu. Het gaat hierbij om uitspoeling van stikstof en fosfaat in bodem en water en uitstoot van emissies in de lucht. Een betere toepassing en benutting van dierlijke mest kunnen deze problemen verminderen. Het doel van dit proefschrift is om de economische, sociale en milieu-technische duurzaamheid van mestverwerking te analyseren en een management-ondersteunende tool te ontwikkelen voor het duurzaam omgaan met dierlijke mest in Nederland. De mestverwerkingstechnieken hebben in dit proefschrift betrekking op mestscheiding en mestvergisting.

Ondanks een toenemende interesse in deze technologieën, is de toepassing ervan in Nederland nog beperkt. Hoofdstuk 2 bestudeert de factoren die van invloed zijn op de investeringsbereidheid van Nederlandse melkveehouders in technologie om dierlijke mest te scheiden. Resultaten laten zien dat met name demografische en sociaal-economische factoren zoals leeftijd en opleiding van belang zijn. Ook de huidige toepassing van de mest op het bedrijf speelt een rol. Eigenschappen van mestscheiding die melkveehouders als belangrijk ervaren zijn de waarde en bruikbaarheid van het eindproduct, het optimaal kunnen benutten van stikstof en fosfaat, en de potentieel te behalen milieuwinst. 51% van de melkveehouders ziet mestscheiding niet als een relevante strategie voor de toekomst. Deze (relatief lage) investeringsbereidheid bepaalt mede het succes van mestscheiding als antwoord van de veehouderij op de toenemende milieuzorgen.

Bij investeringen in mestvergisting speelt verwachte winstgevendheid een belangrijke rol. Het proces van vergisting levert, naast biogas, ook het zogenaamde digestaat op. Een goede en verantwoorde afzet hiervan bepaalt mede de winstgevendheid en het milieutechnische succes van het hele proces. In hoofdstuk 3 is een optimaliseringsmodel ontwikkeld om de economische prestaties van mestvergisting op bedrijfsniveau te analyseren. Dit is gedaan voor 2 beleidsscenario's. In het eerste scenario wordt digestaat beschouwd als kunstmestvervanger ("groene kunstmest"). Het tweede scenario richt zich op de subsidies die worden verschaft voor de productie van groene energie. Analyses zijn uitgevoerd voor Green Power in Salland. Dit bedrijf heeft een inputcapaciteit van 70.000 ton per jaar, produceert elektriciteit en warmte via warmtekrachtkoppeling (WKK) en "levert" drie soorten digestaat: een vaste fractie (FF), ultra-filtraat (UF) en een omgekeerde osmose concentraat (RO). RO wordt momenteel nog beschouwd als dierlijke mest. Het eerste scenario laat echter zien dat als RO als kunstmestvervanger wordt beschouwd, het niet alleen winstgevend is voor Green Power maar ook leidt tot lagere transportkosten en minder milieu-impact vanwege de toepassing ervan op bedrijven in de buurt van de vergister. In het tweede scenario komt naar voren dat het vergisten van mest in combinatie met een WKK niet winstgevend is zonder subsidies.

In hoofdstuk 4 is het effect van onzekerheid rond technische en economische parameters van mestvergisting in kaart gebracht. Dit is gedaan voor de productie van groen gas en sluit aan bij het initiatief van de Nederlandse zuivelketen om op een efficiënte manier groene energie te produceren en te gebruiken. Hiervoor is een stochastisch simulatiemodel ontwikkeld. Dit model simuleert de productie van 17 PJ per jaar aan groene energie op basis van twee business modellen: een model waarbij productie en opwaardering van het groene gas binnen één bedrijf plaatsvindt, en een model waarbij groen gas van twee bedrijven centraal wordt opgewaardeerd. Resultaten laten zien dat de kans op een negatieve netto contante waarde 46% is voor de “stand-alone situatie” en 42% voor het model met centrale opwaardering.

Hoofdstuk 5 breidt voorgaande analyses uit door ook milieutechnische en sociale criteria van mestscheiding en –vergisting mee te nemen. Hiervoor zijn diverse methodieken uit de multi-criteria decision making (MCDM) gebruikt, te weten multi-objective programming (MOP), compromise programming (CP) en goal programming (GP). Ook zijn de voorkeuren van verschillende partijen voor de diverse criteria meegewogen. Geanalyseerde criteria zijn het saldo, broeikasgasemissies, ammoniak-emissies en verandering van landgebruik. Betrokken partijen zijn de lokale overheid, veehouders en een zuivelverwerker. De case-studie betreft de relatief veedichte regio Salland die zich onder meer als doel heeft gesteld een deel van de aanwezige mest te gebruiken voor de productie van groene energie. Resultaten laten een duidelijk conflict zien tussen het saldo en de overige drie criteria: het hoogste saldo gaat samen met hoge ammoniak-emissies, veel veranderingen in het landgebruik en lage besparingen van broeikasgasemissies. Ook tussen de laatste twee criteria treden conflicten op: hoge besparingen rond broeikasgasemissies vragen veel veranderingen in landgebruik, terwijl weinig veranderingen in landgebruik ook maar lage besparingen van broeikasgasemissies opleveren. Voor wat betreft de voorkeuren van de verschillende partijen voor de vier criteria blijken onderling grote verschillen te bestaan. Voor de lokale overheid is reductie van broeikasgasemissies het belangrijkste, terwijl dit voor veehouders en de zuivelindustrie respectievelijk een zo klein mogelijke verandering in landgebruik en een zo hoog mogelijk saldo zijn. Rekening houdend met de onderlinge conflicten tussen de criteria en de verschillen in voorkeuren tussen de diverse partijen is een compromis-oplossing ontworpen voor de verwerking van mest in Salland.

Hoofdstuk 6 vat de gebruikte methodes en data samen en bediscussieert implicaties voor beleid en bedrijfsleven. De belangrijkste conclusies van dit proefschrift zijn:

- De investeringsbereidheid van melkveehouders in mestscheiding op het bedrijf wordt bepaald door socio-economische en demografische eigenschappen van de veehouder maar ook door zijn/haar attitude ten aanzien van specifieke kenmerken van de technologie. Het gaat hierbij om de waarde van het eindproduct, het optimaal kunnen benutten van stikstof en fosfaat en de potentieel te behalen milieuwinst. 51% van de melkveehouders ziet mestscheiding niet als een relevante strategie voor de toekomst.
- Onder de huidige wetgeving, die het omgekeerde osmose concentraat uit mestverwerking beschouwt als dierlijke mest, in combinatie met de lage waarde van digestaat en warmte, zijn investeringen in mestvergisting in combinatie met warmtekrachtkoppeling naar verwachting niet winstgevend zonder subsidies.
- Ondanks de huidige subsidies voor de productie van groen gas uit mestvergisting is de kans op een negatieve netto contante waarde (NCW) substantieel. Als namelijk rekening wordt gehouden met de onzekerheden rond technische en economische parameters van mestvergisting en de productie van groen gas heeft een bedrijf met een eigen opwaarderingsinstallatie een kans van 46% op een negatieve NCW. Als twee bedrijven samenwerken met één centrale opwaarderingsunit daalt deze kans naar 42%.
- Op het gebied van mestverwerking is het lastig om economische, sociale en milieutechnische criteria tegelijkertijd te optimaliseren. Zo treedt er een conflict op tussen het besparen van broeikasgasemissies en het beperken van veranderingen in het landgebruik: hoge besparingen vragen meer veranderingen in het landgebruik, en weinig veranderingen in het landgebruik leveren ook maar lage besparingen van broeikasgasemissies op.
- Verschillende partijen rond mestverwerking hebben verschillende en elkaar tegensprekende voorkeuren. Zo hecht de lokale overheid de grootste prioriteit aan reductie van broeikasgasemissies, terwijl veehouders en de zuivelindustrie respectievelijk een zo klein mogelijke verandering in landgebruik en een zo hoog mogelijk saldo prefereren.

Publications

Refereed scientific papers

Gebrezgabher, S.A., Meuwissen, M.P.M, Oude Lansink, A.G.J.M., 2012. Energy-neutral dairy chain in the Netherlands: An economic feasibility analysis. *Biomass and Bioenergy*, 36: 60-68.

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Conference contributions and other publications

Hoop, D.W. de, Lakner, D., Cooten, W.C. van, Hoop, J.G. de, Bikker, A.M., Prins, H., Gebrezgabher, S.A., Meuwissen, M.P.M., 2011. Kansen op de mestmarkt door mestscheiding en voeraanpassingen Den Haag: LEI, onderdeel van Wageningen UR, (LEI-rapport, onderzoeksveld Sector & Ondernemerschap 2010-083).

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Gebrezgabher, S.A., Meuwissen, M.P.M., Oude Lansink, A.G.J.M., 2009. Economic analysis of anaerobic digestion- A case of Green Power biogas plant in the Netherlands. In: IFMA 17 international conference, Food Fiber and Energy for the future. 19-24 July, 2009, Bloomington, Illinois, USA.

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About the author

Solomie A. Gebrezgahber was born on August 21, 1981 in Asmara, Eritrea. In 2005, she finished her bachelor degree in Accounting from Mekelle University in Ethiopia. From 2002 till 2005, she worked as a graduate assistant in Mekelle University. In 2007, she finished her master's degree in Business Economics from Wageningen University in the Netherlands. Her master thesis focused on assessing the economic feasibility of bioenergy. Later in 2007, she was employed by the Business Economics Group at Wageningen University as a junior researcher which became part of her PhD work. In 2009, she was awarded the WUR strategic fund, IPOP Biobased Economy for a PhD research. During this PhD research, she followed her education program at the Wageningen School of Social Sciences (WASS) and visited the Technical University of Madrid in Spain as a visiting researcher. Her PhD work has been presented in international conferences and published in peer reviewed journals. From February 2012 she has joined the International Water Management Institute (IWMI) as a postdoc.

Completed Training and Supervision Plan

Description	Department/ Institute	Year	ECTS*
A) Project related competences			
Advanced Agricultural Business economics	BEC, WU	2008	6
Econometrics	AEP, WU	2009	6
Advanced econometrics	AEP, WU	2009	6
Advanced bio-economic modelling	WASS, WU	2009	1.5
Theories and models of environmental economics	ENR, WU	2010	6
Agricultural and natural resource management: A multi-criteria approach	WASS, WU	2010	1.5
PhD discussion group-BEC	BEC, WU	2008-12	4
B) General research related competences			
Introduction course	MG3S, WU	2009	1.5
ICABR conference, the emerging bio-economy, Italy		2009	1
IFMA conference, Food, fiber and energy for the future, Illinois, USA		2009	1
EAAE seminar, External cost of farming activities, Chania, Greece		2010	1
C) Career related competences/personal development			
Project and time management	WASS, WU	2011	1.5
Techniques for writing and presenting scientific paper	WASS, WU	2009	1.2
Using voice in public presentation	BEC/ORL, WU	2011	0.5
Computer lab: Food safety economics	BEC, WU	2010	0.5
Computer lab: Advanced supply chain management	BEC, WU	2010	0.5
Total (minimum 30 ECTS)			33.7

*One ECTS on average is equivalent to 28 hours of course work

Financial Support

The research described in this thesis was financially supported by the WUR strategic fund IPOP Biobased Economy, Agricultural Economics Research Institute (LEI), Senternovem and WASS scholarship and junior researcher grant.

Publisher

Ponsen & Looijen BV, Wageningen