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Report 372

Environmental assessment of untreated manure use, manure digestion and co-digestion with silage maize

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WAGENINGEN UR

Colophon

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Wageningen UR Livestock Research and Central Veterinary Institute of Wageningen UR, both part of Stichting Dienst Landbouwkundig Onderzoek (DLO Foundation), together with the Department of Animal Sciences of Wageningen University comprises the Animal Sciences Group of Wageningen UR (University & Research centre).

Single numbers can be obtained from the website.

Abstract
This report describes the environmental impact of untreated manure use, manure digestion, and co-digestion with silage maize for energy production. The life cycle assessment methodology was used. Environmental indicators included were, global warming potential, energy use, eutrophication, acidification and land use expressed per ton applied product. Digestion of manure and co-digestion with silage maize resulted in an improved energy and greenhouse gas balance. However, compared to the use of untreated manure, acidification potentials seemed to increase when digesting only manure and decrease with co-digestion. Overall (co)-digestion of manure and co-substrates presents an opportunity to sustainably produce renewable energy and reduce greenhouse gas emissions. Further analysis is required to fully understand the effects on land use changes when using different co-substrates on a large scale.

Keywords
Anaerobic Digestion, Life Cycle Assessment, Global Warming Potential, Energy Production, Manure Management

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Preface

This research was initiated as a part of the EU-AGRO-BIOGAS project. The overall project aims to improve the yield of medium to large scale biogas plants in Europe via adjustments in planning, substrate pre-treatment and use, and technological developments and monitoring of the biogas production process. The consortium consists of several EU partners and is led by the University of Natural Resources and Applied Life Sciences (BOKU) in Vienna, Austria. As a partial requisite for workpackage 7 a carbon footprint analysis has been conducted comparing different management changes in the installation of the plants and their effect on the emissions of greenhouse gases as an indicator for environmental impact. This research was initiated as an addition to assess the impact of overall energy production from (co)-digestion of manure and by-products and other environmental indicators, such as, eutrophication and acidification. The authors hope this will add to the understanding and knowledge of the environmental consequences of using manure and co-substrates in the production of renewable energy.

For more information about the EU-AGRO-BIOGAS project we forward you to the website: http://www.eu-agrobiogas.net

On behalf of the authors,

Jerke de Vries

Summary

Renewable sources for energy production have been and will continue to be of great importance for the supply of the world' s energy demand. (Co)-digestion of manure with co-products and co-substrates is considered as sustainable due to the possibility to mitigate carbon emissions while producing energy and providing improved fertilizing materials for crop production. However, when viewing the production chain from a life cycle perspective, including co-substrates, it is uncertain whether anaerobic co-digestion gives a true advantage from an environmental perspective. The goal of this study was to provide insight in the environmental impact between using 1. untreated manure, 2. digested manure, and 3. digestate from co-digestion of manure with co-substrates. The life cycle assessment methodology was used to maintain a life cycle perspective and comparison.

The study focused on a general farm scale situation where manure is applied without treatment, digested or co-digested. Dairy cattle manure and silage maize were used as substrates for digestion. Overall, three scenario's were constructed: 1. the use of untreated manure (scenario 1), 2. the use of digestate from digesting only manure (scenario 2), and 3. the use of digestate resulting from co-digestion of manure and silage maize in a 50:50 fresh matter ratio (scenario 3). Environmental indicators assessed were: global warming potential (kgCO_2-equivalents (eq)), acidification potential (kgSO_2-eq), eutrophication potential (kgN-eq), and land use (m^2). The scenario's were compared on the basis of a functional unit of 1 ton of applied product (untreated manure or digestate). System boundaries were located from the manure storage until the application of untreated manure or digestate. Emissions after application were included. Production of silage maize and all related inputs were included inside the boundary. Two models were used to perform the study. A model was created in SimaPro for the assessment of using untreated manure and digesting only manure. E-CROP was used to model the production and digestion of silage maize. The results for co-digestion were calculated by combining both models.

Results showed that the use of untreated manure caused an emission of approximately 149 kg CO_2-eq per ton applied product whereas this was 101 and -3.9 kg for scenario 2 and 3 respectively. Lower methane production in the manure storage was the main reason for the lower greenhouse gas emissions (GHG) in scenario 2. In the case of scenario 3 this was mainly due to higher energy production and thus replacing more fossil electricity. Net energy used in the scenario's 1, 2 and 3 was: 159, 100, and -382 MJ per ton applied product respectively. In both cases N_2O emissions decreased due to the replacement of mineral fertilizer.

Acidification potentials varied from 2.2 for scenario 3 to approximately 2.9 kgSO_2-eq for scenario 2. Ammonia added most to the acidification potential. Silage maize has lower related ammonia emissions during production compared to the storage of manure prior to digestion and therefore co-digestion resulted in a lower acidification potential. Slightly higher ammonia emission from digested manure compared to untreated manure resulted from a higher mineral N content after digestion.

Eutrophication potentials varied from 0.69 – 0.83 kgN-eq. Co-digestion resulted in lowest eutrophication potential whereas the use of untreated manure had the highest potential. This was caused mainly by differences in nitrate emissions.

Land use was defined as the area needed to produce the co-substrate. For 1 ton of applied product in the case of co-digestion, 0.39 tons of fresh matter silage maize was required using 0.0112 ha of land.

Overall, uncertainty was not assessed. However, the results indicate that the digestion of manure and especially co-digestion of manure with silage maize led to a lower emission of CO_2-eq compared to the use of untreated manure. Co-digestion presented the lowest emission of GHG's combined with high energy production. The acidification potential did not change considerably when digesting only manure. When co-digestion took place, the acidification and eutrophication potential tended to decrease. In conclusion, co-digestion of manure and co-substrates represents the potential to reach the environmental goal of providing renewable energy in a sustainable manner. However, other implications, such as, indirect land use change and long term carbon sequestration, when using digestate as fertilizer, should be considered further for decision making.

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1 Introduction

1.1 Background

Renewable sources for energy production have been and will continue to be of great importance for the supply of the world' s energy demand. (Co)-digestion of manure with co-products and co-substrates is considered as sustainable due to the possibility to mitigate carbon emissions while producing energy and providing improved fertilizing materials for crop production (Amon *et al.*, 2007). The technology has expanded in the last decade over many European countries (Weiland *et al.*, 2003). The anaerobic digestion, or fermentation, of manure with co-substrates for electricity production is considered to not add to the net CO_2 emission and therefore does not add to the global warming effect. However, when viewing the production chain from a life cycle perspective, including co-substrates, it is uncertain if anaerobic co-digestion gives a true advantage from an environmental perspective. Anaerobic digestion has been studied from a systems perspective for several industrial applications (Verstraete *et al.*, 1996; Mata-Alvarez *et al.*, 2000; Eriksson *et al.*, 2005). Only few whole system considerations, including different environmental indicators, of anaerobic digestion in agricultural systems have been made or have been focusing only on a few elements of ecological sustainability (Berglund *et al.*, 2006; Clemens *et al.*, 2006). Therefore insight is required in how anaerobic co-digestion of manure with co-products affects the environment considering other environmental indicators as well.

1.2 Problem

It is unknown what the impact on the environment is when digesting manure or co-digesting manure with co-substrates compared to using untreated manure when looking from a life cycle perspective and including several environmental indicators.

1.3 Research questions

A general research question was formulated:
What is the environmental impact of digesting manure and co-digesting manure with co-substrates compared to using untreated manure when looking from a life cycle perspective?

Sub-questions
1. What is the environmental performance when no digestion takes place and where untreated manure is applied to the field directly?
2. What is the environmental performance when digestion of only manure takes place in the system?
3. What is the environmental performance when digestion of manure with additional co-substrates takes place in the system?

1.4 Life Cycle Assessment

In order to answer the research questions and give a complete overview of the environmental performance, the Life Cycle Assessment (LCA) methodology will be used. LCA is a methodology to model the complex interactions between a production chain and the environment. It has been applied in determining the environmental impact of different agricultural systems (Cederberg *et al.*, 2000; de Boer, 2003; Dalgaard, 2007; Thomassen *et al.*, 2008). The overall ISO-14040 standard will be followed including the following phases: 1. Goal and scope definition, 2. Life cycle inventory, 3. Life cycle impact assessment, and 4. Interpretation. The report follows these phases from Chapter 2 onwards to Chapter 4 with the discussion and conclusions reported in Chapter 5.

2 Goal and scope definition

2.1 Goal and scope

The specific goal of this research is to analyze and compare the environmental impact of (co)-fermentation of manure with co-substrate maize. In this study three general scenarios are considered:

1. A reference situation without fermentation where untreated manure is applied to the field and no production and fermentation of manure with co-substrates is considered.
2. A situation where only manure is digested and the digestate is directly applied to the field.
3. A situation when silage maize is added as a co-substrate during digestion and the digestate is directly applied to the field.

Furthermore, the aim of this research was to apply the software SimaPro 7.1 (Pré-consultants, the Netherlands) and use the Ecoinvent Database v.2.0 (EcoinventCentre, 2007).

The LCA will be focusing on a ‘general analysis’ providing a report for informing purposes. No decisional processes will be directly connected to the results. Further elaboration will take place in section 2.4 when the system boundaries are considered. Concerning the comparative nature of the study an attributional approach will be applied for the analysis considering only average data (Thomassen *et al.*, 2008; JRC, 2009).

Several environmental indicators where selected:

- Fossil energy use expressed in MJ.
- Global warming potential (GWP) including: CO_2, CH_4 and N_2O emission expressed as kg CO_2-equivalents.
- Eutrofication potential (NOx, NH_3, NO_3^-, NH_4^+, P_2O_5 and PO_4^-) expressed in kg N-equivalents.
- Acidification potential (SO_2, NOx and NH_3) expressed as kg SO_2- equivalents.
- Land use expressed as m^2 per functional unit.

The research is a part of the EU-AGRO-BIOGAS project, specifically workpackage 7, in which a carbon footprint study has been conducted for differentiation in management options of current biogas production units. This research will have a more general focus in order to compare different scenario’s and will therefore be based on general and average data.

The study focuses on Western Europe as a geographical region. It was performed by the Animal Sciences Group and Plant Research International both part of Wageningen University and Research Centre.

2.2 Functional Unit

The service of the system in the reference situation is the handling of manure. In the case of fermentation energy is produced which forms the main service, however the handling of the digestate also has to take place. In order to compare the three situations the results will be expressed per ton of applied product as functional unit (FU). It is assumed that no further processing after digestion takes place.

2.3 Materials

2.3.1 Models and data

The environmental assessment was performed using Simapro 7.1 (PreConsultants B.V., the Netherlands) software combined with the Ecoinvent 2.0 database (EcoinventCentre, 2007). Required data were gathered from literature and expertise. No physical experiments were done in this research. The E-CROP model was used to generate the results for crop production and transport and the digestion of only silage maize (Corré *et al.*, 2008). A model for untreated manure handling and manure digestion was created in SimaPro. In the case of co-digestion, both model outcomes were combined. Further elaboration will take place in Chapter 3.

2.3.2 E-CROP

E-CROP was used for calculations of energy use and GHG emissions during crop production, transport and the conversion to electricity by digestion of silage maize. The model was developed in the past years to assess a number of sustainability aspects of biomass and bioenergy chains (Corré *et al.*, 2008; Conijn *et al.*, 2009). The model consists of two parts: a simulation module calculating crop production on the basis of agricultural inputs and soil and climatic conditions and an energy and GHG balance calculation module. The two parts work independently. Balance calculations can be made on the basis of statistical, practical or experimental data. For this report balances were calculated on the basis of average yields and average agricultural input levels for silage maize in the Netherlands

2.3.3 Impact assessment method

The ReCiPe v. 1.03 method was used to conduct the Life Cycle impact Assessment (Goedkooop *et al.*, 2009). Fresh water eutrophication was added to the terrestrial eutrophication impact to create one eutrophication impact. Units from P-equivalents were converted to N-equivalents on the basis of Heijungs (1992) and (Guinée *et al.*, 1992). Final impact factors for phosphorus holding compounds are addressed in Table 2.1.

Table 2.1 Impact assessment factors for phosphorus holding compounds

Compound	P-equivalents (original)	N-equivalents (used)
Phosphate (PO_4^{3-})	0.33	2.38
Phosphorus (P)	1	7.29
Phosphorus Pentoxide (P_2O_5)	0.44	3.19

2.4 System boundaries and approach

The LCA focuses on a farm scale fermentation plant. The plant exists of one digestion unit and a storage for the digestate. Furthermore, in the case of manure digestion, it is assumed that the digester is located on the same farm and therefore no transport is accounted for the manure. Main characteristics of the installation are taken from Timmerman *et. al.* (2005). That research was conducted on two experimental farms in the Netherlands, one digesting pig manure and another digesting cattle manure. The layout of the dairy farm will be used as a guideline for the collection of data.

Dairy cattle manure was the only substrate in the reference scenario and in the case of digesting only manure. For co-digestion, maize silage was considered as co-material next to cattle manure since this co-material is widely used for the production of energy from anaerobic co-digestion (Weiland *et al.*, 2003). Dairy cow manure was assumed as an input from animal production. The animal production system itself was not accounted for in this research because it was expected that there will be no changes in the system when studying the different scenario's. The boundary will be at the point where the manure reaches the storage system inside the housing. In general, shorter in-house storage times will occur in order to yield more methane in the digester (de Mol *et al.*, 2004). This will be considered in the assessment. Direct and indirect emissions after application of manure and digestate are taken into account. The effects of the possible reduction of soil carbon through the use of digestate instead of untreated manure will not be considered in this research.

Attributional LCA was applied as discussed in section 2.1. In attributional LCA, allocation is used to include a part of the respective environmental impact of the production process of a product to the system. However, due to the use of only full products in this study, no allocation had to take place.

Figure 2.1 presents a schematic overview of the system under study with its applied boundaries. All included processes will be analyzed for the above mentioned environmental impacts including the background process, e.g., electricity use and production, fuel use and production.

Capital goods were not considered inside the system to be studied since it is expected that they will not significantly affect the final result (Audsley *et al.*, 1997).

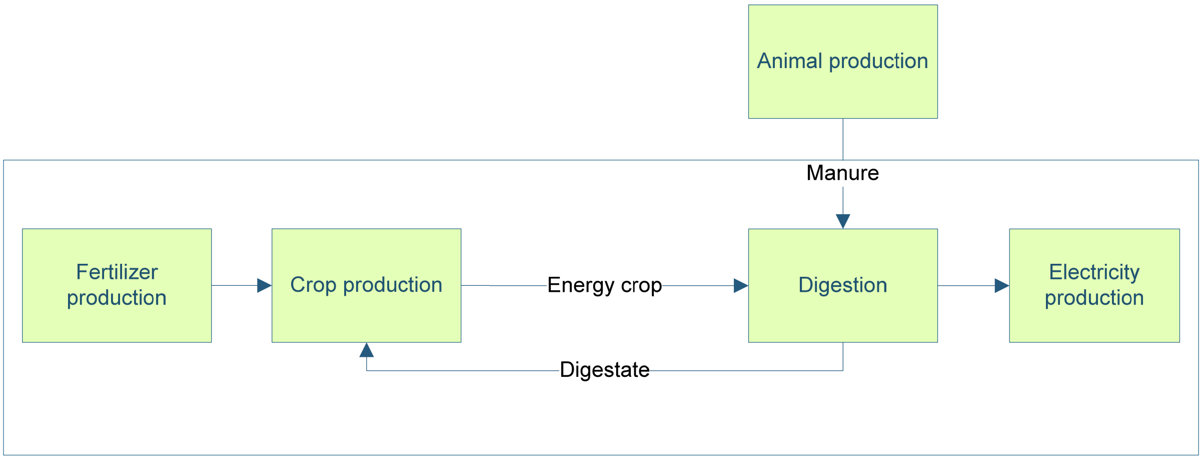

Figure 2.1 General flow diagram of the system and the additional system boundaries

Data should be case specific where possible. However, when not available, data from other inventories were used. The quality of the data is discussed where applicable in the next section.

Overall, the modeling of the scenario's was conducted by using the two models, E-CROP and the manure digestion model. The reference scenario was modeled without applying digestion. In the case of co-digestion of manure and silage maize an input ratio of 50:50 on fresh weight basis was assumed. The results from both models for 1 ton of applied product were used and averaged to come to the impact for co-digestion. E-CROP only models greenhouse gas emissions (GHG) and therefore emissions of NH_3, NOx, NO_3 and P_2O_5 from digestate storage and application were calculated additionally. Overall emission factors were used to obtain this (Chapter 3).

3 Life cycle inventory

In the life cycle inventory, data are collected with in- and outputs related to the processes of the studied life cycle. The final output of this chapter contains all data relevant for the analysis. All basic choices considering allocation, system expansion and boundaries are described.

3.1 Description of scenario's

3.1.1 Reference Scenario

The reference scenario consists of the storage, transport and application of cow manure as shown in Figure 3.1. Fuel- and electricity requirements are included in the inventory. For all schematic overviews of the scenario's the storage processes have been left out in order to simplify the scheme. In general after each process the product(s) are stored.

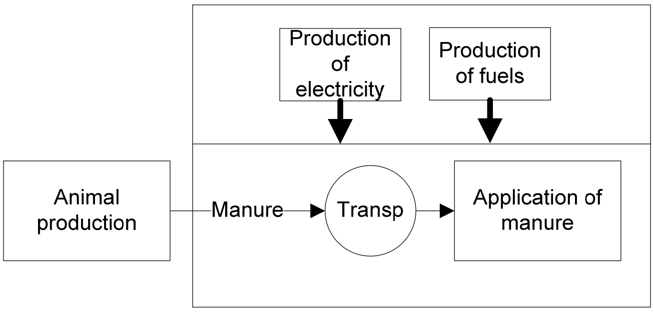

Figure 3.1 Reference scenario with transport and application of manure to the field

Furthermore, it was assumed that the manure was used to fertilize a standard farm in the Netherlands with grass and maize. Additional mineral fertilizer that is used in the reference scenario is included. The emissions from fertilizer production and transport are therefore included in the inventory.

Several assumptions were made for the reference scenario. These assumptions describe the type of animal housing, the method of storage, the method of application and common data required for the calculations. During this definition phase a more typical system was described instead of an average system. The following was defined:

- A standardized dairy farm on sandy soil for the Netherlands was used to represent the fertilization strategy applied (Table 3.1). The standard farm is defined in another research and was based on national available data (de Vries *et al.*, 2009). Table 3.3 presents the composition of cow manure. The overview in Table 3.1 shows that when applying 1 kg of effective nitrogen, this is the amount of nitrogen taken up by the crop after losses are deducted, 48% results from animal slurry and 52% from mineral fertilizer. Therefore, when applying 1 ton of manure after storage, 2.24 kg of effective nitrogen is applied when using 60% effective N in cow slurry (DR, 2009). In addition, 2.24 x 48/ 52 = 2.07 kg effective N is applied from mineral fertilizer (ammonium nitrate). Furthermore, the same calculation holds for phosphorus application. No potassium was applied from mineral fertilizer since the requirement is nil (Table 3.1).
- Animal manure is stored in a manure pit under the animal housing before it is pumped and stored into a covered outside storage. The main housing system applied is cubicle housing with slatted floors, based on liquid manure, and limited grazing (de Mol *et al.*, 2004). With limited grazing 60% of the excreted manure is collected in the storage system during summer. Pumping of the slurry into the outside storage system occurs approximately every month.
- The slurry is stored during the winter when application is prohibited. During the growing season (March – September) manure is applied from the manure storages (de Mol *et al.*, 2004). The slurry is applied by using a manure injector, injecting the slurry into the soil. At this moment, this is the most common practice for manure application.

Table 3.1 Fertilization on a standardized dairy farm in the Netherlands. Total amounts and fractions of N, P_2O_5 and K_2O from organic manure and fertilizer.

			Sandy soil	
		Total	Manure	Fertilizer
Cattle incl.	kg effective N/ ha	233	113	120
grazing	kg P_2O_5/ ha	96	86	10
	kg K_2O/ ha	352	352	0

3.1.2 Manure digestion scenario

Figure 3.2 presents the scenario where manure is digested for the production of electricity. In this situation animal manure is again stored under the housing system but now pumped into the digester. The biogas is used in a combined heat and power plant (CHP) to produce electricity. The digestate, digested matter resulting after digestion, is transported to the field and applied. Due to digestion, the retention time in the storage system is shorter and affects the methane emission in storage. This is considered in section 3.2.

The resulting digestate applied in this case has a higher ammonium nitrogen (NH_4^+-N) content compared to the scenario without digestion due to mineralization of organic nitrogen during the digestion process (Pabón-Pereira *et al.*, 2008). This influences the fertilizing capacity to the field and furthermore the leaching of nitrate and emissions of nitrous compounds.

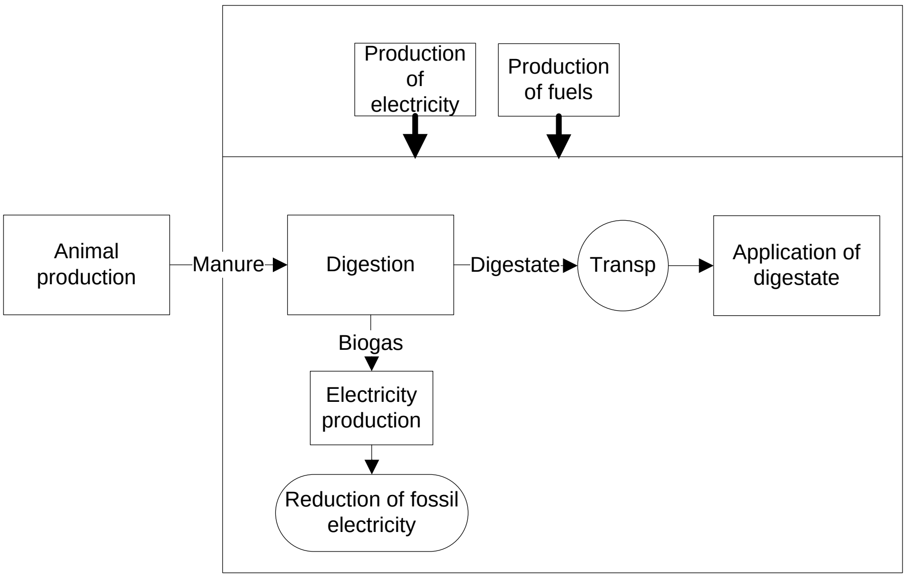

Figure 3.2 Scenario 1 considering the digestion of manure and application of digestate and the production of electricity

The electricity produced through the burning of biogas in a combined heat and power generation unit is considered to reduce the use of the average electricity mix in the Netherlands. The emissions from the production of this electricity is subtracted from the system under study.

3.1.3 Co-digestion of manure and silage maize

Figure 3.3 presents the process tree when silage maize is used as a co-product during digestion. The production, including all required processes such as, soil tillage, seeding, fertilizing, maintaining of the crop, harvesting, and storage of the crop, are included in the study. Due to the addition of crop material to the digestion process, the characteristics of the output material (digestate) changes (Pabón-Pereira *et al.*, 2008). This again influences the fertilizing capacity of the material and the leaching and volatilization of nutrients into the soil and atmosphere.

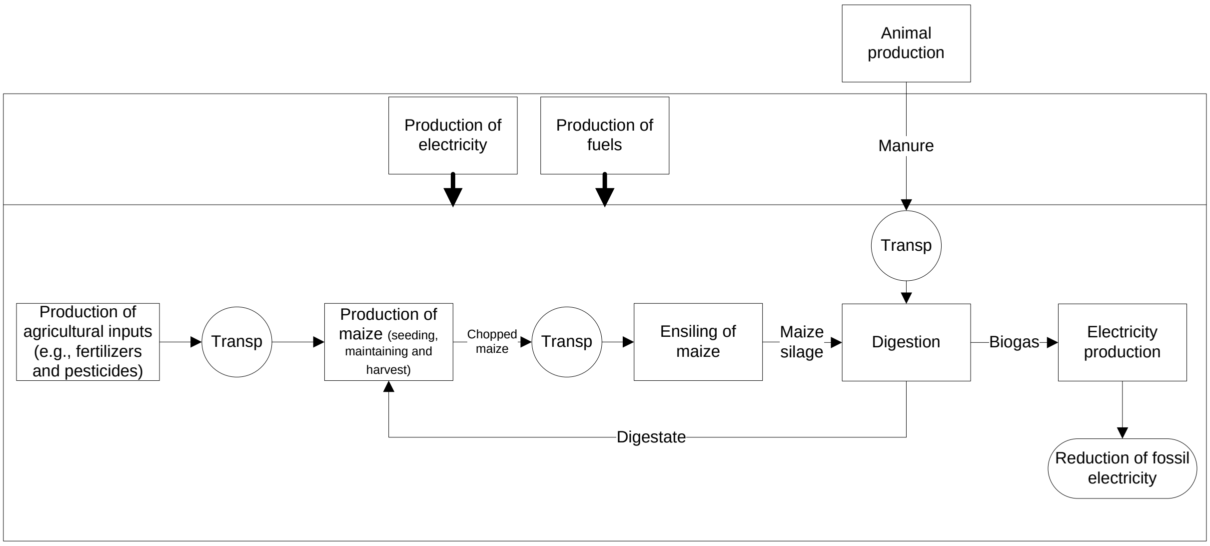

Figure 3.3 Scenario 2 including the production of maize and co-digestion of silage maize and manure

3.2 Data collection

This section describes the data collected for the systems under study. This includes each process mainly for manure handling. For data used in the E-CROP model we refer to Conijn & Corré (2008).

3.2.1 Manure and digestate storage and handling

Manure and digestate are stored after excretion or digestion. Emissions of nitrous oxide (N_2O), ammonia (NH_3), nitrogen oxides (NO) and nitrogen (N_2) occur during storage. Furthermore, methane is emitted. This is accounted for. Table 3.2 presents the emission factors for the storage systems used (Oenema *et al.*, 2000; de Mol *et al.*, 2004; IPCC, 2006). Phosphorus and potassium contents of the manure are assumed to be equal after storage.

Table 3.2 Emissions from housing and outside storages

Storage\ Unit	N_2O-N[1] % of N	NO-N[1] % of N	NH_3-N[2] % of N	N_2-N[2] % of N	Total % of N	CH_4[3] kg/ton manure
In house storage no digestion	0.2	0.1	11.4	1	12.7	1.42
In house storage with digestion	0.2	0.1	11.4	1	12.7	0.471
Oustide storage	0.5	0.1	1	1	2.6	0.092

[1] IPCC (2006)
[2] Oenema *et al* (2000)
[3] Mol en Hilhorst (2004)

Emissions of methane change in the case of digesting due to shorter storage time. It is assumed that this is reduced from 1.42 kg/ton to 0.471 kg/ton (de Mol *et al.*, 2004). However, this only holds when the digestate is stored in a covered storage system where the rest gas potential is utilized (Sommer *et al.*, 2004; Amon *et al.*, 2006). Ammonia and other nitrous compound emissions were assumed to be similar in both cases since for ammonia the overall part is emitted in the first days of storage. Emissions from outside storage apply to untreated cattle slurry as well as digestate.

The pumping of manure and digestate into and from storage system is not included due to the small contribution in the total environmental impact in the chain.

The manure and digestate composition will change after storage. Table 3.3 presents the changed compositions. Part of the dry matter and organic matter is decomposed due to bacterial activity. This results in methane production and the mineralization of nitrogen. However, due to complexity only total nitrogen is considered in the storage analysis instead of total ammonical nitrogen (TAN) contents of the manure. For application emissions TAN was used. Dry matter and organic matter decomposition is estimated at the same rate based on a recent Danish report (Wesnæs *et al.*, 2009). 10% of the dry matter (DM) and organic matter (OM) was lost during in house storage and 5% of DM and OM was lost during outside storage.

Table 3.3 Cow manure composition after excretion, after in house storage and after outside storage

Component	DM	OM	Ntot	P_2O_5	K_2O
Unit	g/kg	g/kg	g/kg	g/kg	g/kg
After excretion	86	64	4.4	1.6	6.2
After in house storage	76	57	3.84	1.6	6.2
After outside storage	72	54	3.74	1.6	6.2

The mineral nitrogen content of untreated manure was assumed to be 50% of total N (KWIN, 2009-2010). For digestate resulting from digestion of manure and co-digestion this was assumed to be 57% based on Timmerman *et al* (2005). It was assumed that phosphorus and potassium compositions did not change.

3.2.2 The digestion process

During digestion organic matter is decomposed and transformed into biogas and several other components (Pabón-Pereira *et al.*, 2008). Furthermore, organic nitrogen will be mineralized to inorganic nitrogen, which is directly plant available. 60% of the nitrogen in cow slurry is regarded as effective nitrogen on the long run (DR, 2009). After digestion this is considered to be 78% (Nielsen *et al.*, 2002). This change in effective nitrogen will affect the fertilization capacity of the product. This has been taken into account. The total effective N required is the same in both situations, however less mineral fertilizer will be used since more nitrogen is available from the digestate. Further calculations are presented in the next section.

Per kg of organic matter in cattle slurry, $0.17 m^3$ of CH_4 is produced (Timmerman *et al.*, 2005). An energy efficiency of 82% is used with 32% electric efficiency (Timmerman et al, 2009). 33 MJ ton^{-1} of substrate is required for stirring whereas this is 250 MJ ton^{-1} for heat (Berglund *et al.*, 2006). In total 1.5% of the produced methane leaks into the environment, 1% from overall leakage from the installation according to Edelmann (2001) in EcoinventCentre (2007) and 0.5% of methane slip from the gas engine (IPCC, 2006; EcoinventCentre, 2007). The lower heating value (LHV) of methane is 50.1 MJ kg^{-1} with a specific weight of 0.714 kg/m^3.

It was assumed that the electricity required during the digestion process was used directly from the on site production. Electricity usage was subtracted from total production prior to considering the replacement rate of fossil based electricity.

3.2.3 Emissions during and after application

Table 3.4 presents the emissions occurring during and after application of cow slurry and digestate. Prior to calculating these emission, storage emissions were subtracted.

Higher ammonia emissions are expected to occur when applying digestate due to a higher level of mineral nitrogen (Mosquera *et al.*, 2007). The same emission factor of 17% of TAN was used in both cases. Due to a higher TAN content of the digestate, higher ammonia emissions therefore occur. Furthermore, indirect emissions of N_2O from volatilization of NH_3 and NOx and leaching of NO_3 were considered next to the direct emissions of N_2O and NO. Nitrate leaching amounts were based on a recent study comparing different fertilizing materials (Dekker *et al.*, 2009). Phosphorus leaching is difficult to determine due to the immobility of phosphorus in the soil, the dependency on many different soil conditions etc. Therefore, one emission factor was applied to all phosphorus applications based on the EDIP method from Denmark. The emission rate was assumed to be 0.6% of P applied (EPA, 2003).

Table 3.4 Emissions during and after application of cow slurry and digestate (IPCC, 2006; Stehfest *et al.*, 2006; Dekker *et al.*, 2009; Velthof *et al.*, 2009; Wesnæs *et al.*, 2009)

	Direct				Indirect		Leaching
	N_2O-N[1]	NO-N[2]	NH-N_3[3]	Total N	N_2O-N[1]	N_2O-N[1]	NO_3[4]
Unit	% of N	% of N	% of TAN	% of N	% of NH_3-N & NOx-N	% of N leached	% of N
Cow slurry	1	0.55	17	18.6	1	0.75	21
Digestate	1	0.55	17	18.6	1	0.75	19
Ammonium Nitrate	1	0.1[5]	2.5	3.6	1	0.75	19.7

[1] IPCC (2006)
[2] Stehfest & Bouwman (2006)
[3] Velthof *et al* (2009)
[4] Dekker *et al* (2009)
[5] 0.1 x N_2O Wesneas *et al* (2009)

Emissions related to the application of mineral fertilizer were calculated using the process 'Fertilizing by broadcaster' in Ecoinvent. The amount of ha fertilized when one ton of manure is applied was calculated based on the fraction of effective N and P_2O_5 applied from fertilizer (Table 3.1). This resulted in 0.028 ha in the reference situation and 0.0194 in the manure digestion scenario.

When applying 1 ton of untreated cattle manure 2.24 kg (3.74 * 0.6) of effective nitrogen and 1.6 kg of P_2O_5 is applied. In addition 2.07 kg effective N from ammonium nitrate and 0.0176 kg of P_2O_5 from tripelsuperphosphate is applied (see calculation under reference scenario description). Transport distances of 50 km were assumed based on (Dekker *et al.*, 2009) and Ecoinvent. Since the process in the database includes a transport distance to the regional storehouse not the full distance (150 km) as described by Dekker *et al* (2009) has been taken into account.

When manure digestion takes place the higher mineral nitrogen content is assumed to replace more fertilizer. In this case a higher effective N content (78%) was assumed to avoid an additional 0.67 kg of nitrogen from mineral fertilizer. It was assumed that no additional phosphorus was replaced.

4 Life cycle impact assessment and interpretation

In this chapter the results and the interpretation will be discussed. The results for the different scenario's will be presented in the same graphs for every environmental impact.

4.1 Global Warming Potential

Figure 4.1 presents the results for global warming potential of the scenario's: 1. the reference situation in which manure is used in untreated form, 2. anaerobic digestion of only manure, and 3. co-digestion of manure and silage maize (ratio 50:50). The GWP of the third situation was determined by combining of the results from the second scenario with the results from the E-CROP program. This led to 2 tons of digestate, i.e., 1 ton of digestate from manure and 1 ton of digestate from silage maize. The outcome was divided by 2 in order to come to a FU of 1 ton applied product.

The use of untreated manure without any form of digestion resulted in a higher emission of CO_2-equivelants (CO_2-eq), around 149 kgCO_2-eq per FU, compared to the situations with digestion of only manure, around 101 kg CO_2-eq. Co-digestion of manure and silage maize led to the lowest emission, even a negative net emission of greenhouse gases, around -3.9 kgCO_2-eq per ton applied product. This was mainly due to the replaced amount of fossil based electricity (778 MJ electric) which led to a negative CO_2 emission. Moreover, lower methane emission occurred due to a shorter retention of manure inside the storage system compared to the reference scenario where manure was stored for a longer period of time (de Mol *et al.*, 2004).

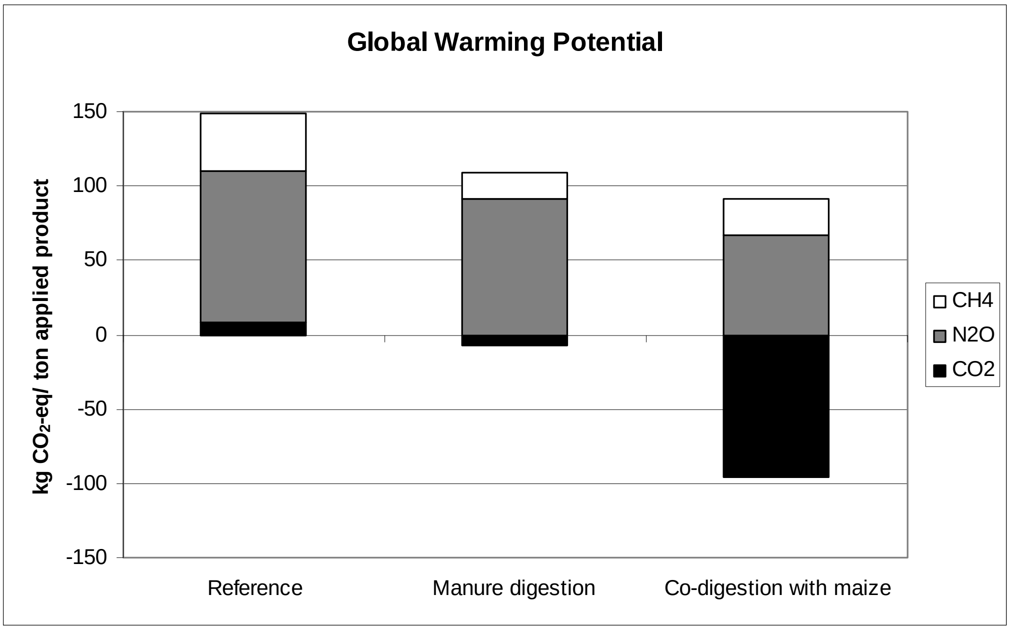

Figure 4.1 Results for the global warming potential of the reference scenario (untreated use of manure), digestion of only manure and the co-digestion of silage maize and manure

N_2O emissions in scenario 1 and 2 where slightly higher compared to the third situation, 102, 90.8 and 67.5 kgCO_2-eq respectively. In scenario 1 and 2 this was due to the intermediate storage of untreated manure from which N_2O was assumed to emit with a rate of 0.5% of total N in the manure according to IPCC (2006). Moreover, N_2O emissions were reduced in scenario 2 and 3 because of the replaced amount of fertilizer. Mineralization of nitrogen takes place during anaerobic digestion resulting in a higher ammonium content in the digestate which is readily available for crop uptake and therewith has a higher fertilizing capacity. Respectively 0.67 and 7.1 kg of N from mineral fertilizer were replaced in scenario 2 and 3 compared to scenario 1.

4.2 Energy balance

The production of energy is a main goal of co-digestion of manure and by-products. Figure 4.2 presents the used, produced and net energy production or consumption of the three scenario's. The net energy use is defined as the total energy used in the chain, including electrical energy for digestion, subtracted with the total electricity production. Heat production was not considered since it was assumed that only the necessary heat for the process was used and residual heat was expelled to the environment.

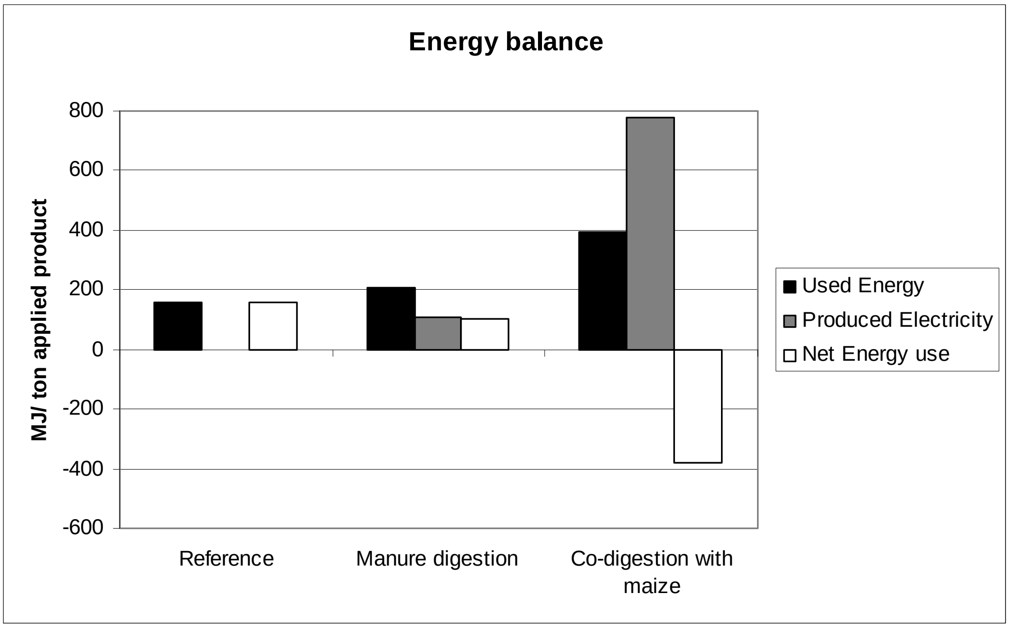

Figure 4.2 Used, produced and net energy use or production for the scenario's. Heat is excluded from the results. It is assumed that only heat was used for the process. Resulting heat is expelled to the environment.

The reference system required around 160 MJ of energy per ton applied product. In case of digesting only manure, 109 MJ of electrical energy was produced whereas 209 MJ of total energy was used. Moreover, when co-digesting manure and silage maize more electricity was produced, approximately 778 MJ. This was mainly due to the high amount of degradable organic matter in the silage maize compared to low degradable organic matter contents in manure, around 287 and 57 gOM/kg fresh material for silage maize and manure respectively. The higher energy use in the third scenario resulted from the energy demand for the production of silage maize, approximately 206 MJ, and during the digestion process. Net energy used was -382 MJ when co-digesting silage maize and manure.

4.3 Acidification potential

The use of manure and digestate before and after co-digestion has a potential acidifying effect on the environment. Main key components contributing to this effect are ammonia (NH_3), nitrous oxides (NOx) and sulfur dioxide (SO_2). Ammonia and some nitrous oxides emitted from manure and digestate storages, whereas sulfur dioxide and some nitrous oxides results from industrial processes and the use of fossil fuels. Sulfur dioxide has not been accounted for in the E-CROP model. It was assumed to be negligible since it only contributes 0.9 and 0.4% of the acidification potential in the reference and manure digestion scenario respectively.

Acidification potentials of the scenarios ranged from 2.2 for scenario 3 to approximately 2.9 kgSO_2-eq for scenario 2 (Figure 4.3). This indicates that the acidification potential is possibly affected by the digestion of manure and/ or co-substrates. Ammonia added most to acidification potential, from 97 –

98% whereas NOx added only 1.7 – 2.4%. NH_3 emissions were lower in the co-digestion scenario due to the use of silage maize as co-substrate. Silage maize has lower related ammonia emissions during production compared to the storage of manure prior to digestion.

The slightly higher ammonia emission in the scenario with only digestion of manure can be explained by the higher mineral N content of the digestate after digestion. The ammonia emission during application is related to the TAN content of the manure (17% of TAN) (Velthof *et al.*, 2009). Since all materials were assumed to have the same emission factor, application of digested manure resulted in a higher NH_3 emission.

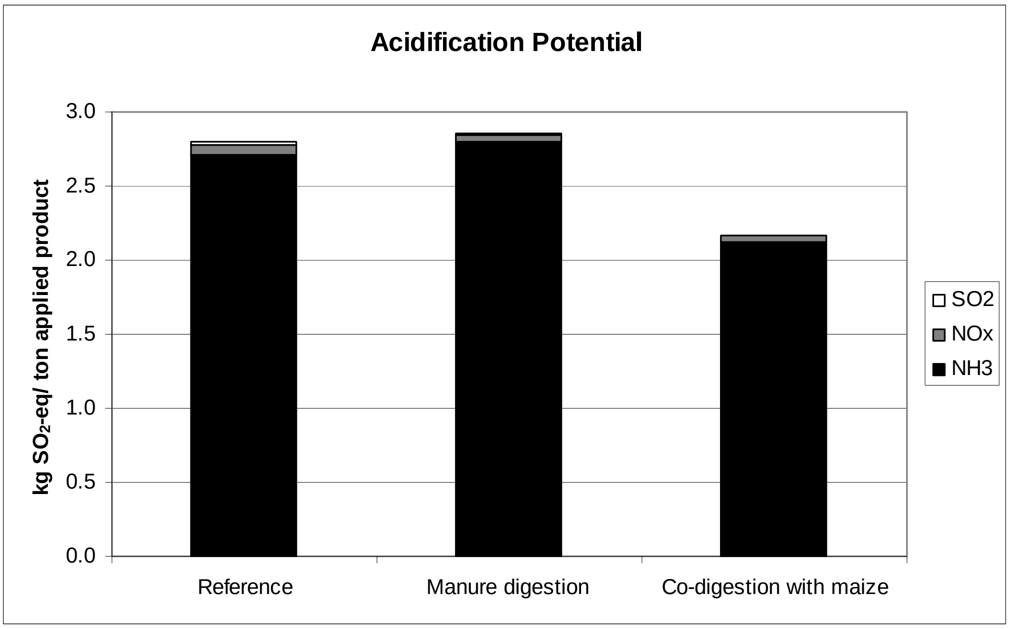

Figure 4.3 Result for the acidification potential of the three scenario's expressed in kg SO_2-equivalents per ton applied product

4.4 Eutrophication potential

Eutrophication of water and terrestrial area has been recognized as a potential problem in the affecting of biodiversity and the nutrient enrichment of poor soils and waters (Schindler, 1977). Main components contributing to this environmental impact are: NO_3^-, PO_4^{3-}, NOx, NH_3 and other N or P components. The use of manure, digestate and mineral fertilizers contribute to the environmental effect of eutrophication.

Figure 4.4. presents the results for the eutrophication potential of the 3 studied scenario's expressed as kgN-equivalents per ton applied product. Overall results varied from 0.69 – 0.83 kgN-eq. Results for the scenario with co-digestion showed the lowest potential whereas the reference system had the highest potential. This difference was mainly due to a lower nitrate emission in the situation of co-digestion. These lower emission rates resulted from more effective nitrogen in the digested manure and co-digested material and thus affecting the emission coefficients of nitrate (21% of N for manure and 19% for digestate, Table 3.4) (Dekker *et al.*, 2009). Furthermore, ammonia emissions where slightly lower due to the reason mentioned under section 4.3. Phosphate (PO_4) emissions are directly related to the production of phosphorus fertilizer (EcoinventCentre, 2007). No phosphorus fertilizer is used during the production of silage maize in the E-CROP model and therefore no phosphate emission occurs. Ammonium emission were assumed to be negligible from maize silage production in the third situation and therefore not considered. In the reference and manure digestion scenario's it only contributed from 0.1 – 0.15% of the total eutrophication potential.

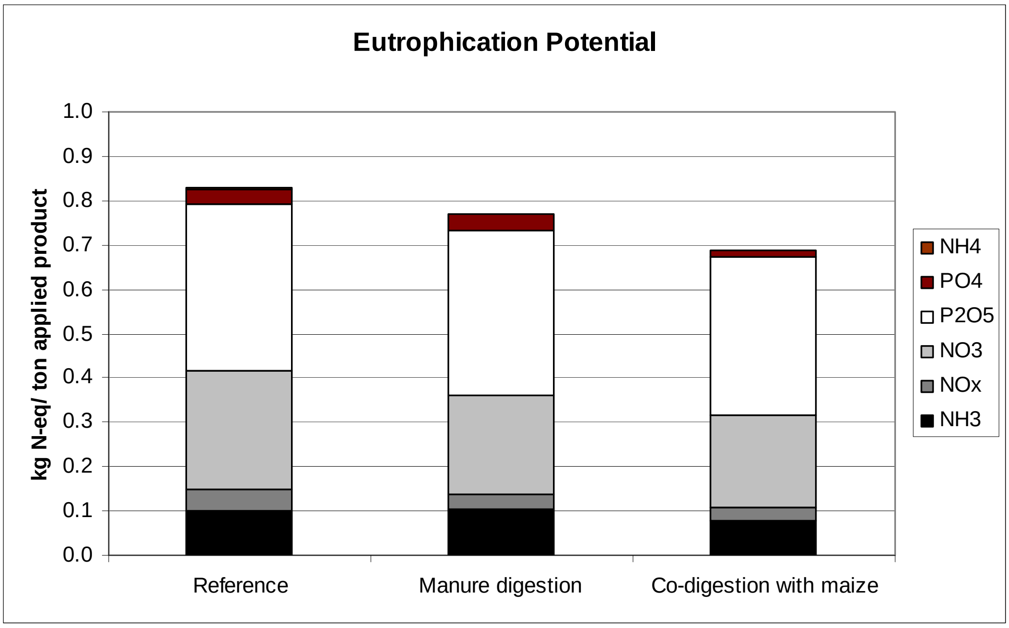

Figure 4.4 Results for the eutrophication potential of the three scenario's expressed in kg N-eq per ton applied product

4.5 Land use

Land use can be considered as the land required to produce the needed co-substrate or by-product used in the digestion process. In this study only silage maize was used as a co-substrate. The required amount of silage maize to form 1 ton applied product from co-digestion (the FU) was 0.39 tons fresh matter. In order to produce this amount, 0.0112 ha of land was required.

5 Discussion and conclusions

5.1 Discussion

Uncertainty
In this study only average data were used and no sensitivity analysis was performed. Therefore, the uncertainty of the results is not fully clear. Main uncertainties will occur through, e.g., variations in emission data and compositions of products. Product composition can differ substantially in practice, e.g., for silage maize and especially manure (Pabón-Pereira *et al.*, 2008). Energy production and the emission of nitrous components are expected to be most sensitive depending on composition and treatment. Moreover the replaced fossil energy source is of great importance to the emission of greenhouse gases. CO_2 emissions can differ substantially between, e.g., coal and gas fired power plants. Coal and gas based electricity in the Netherlands emit approximately 1 and 0.57 kg of CO_2 per kWh electricity produced (EcoinventCentre, 2007). In this study the average electricity mix in the Netherlands was used assuming a reduction of approximately 0.66 kg CO_2 per kWh produced (EcoinventCentre, 2007).

It has been observed that ammonia emissions increased due to the use of digestate (Bosker *et al.*, 2004; Huijsmans *et al.*, 2007). This increases acidification and eutrophication potentials. However, another study has indicated little or no changes in ammonia emission when comparing untreated and digested manures due to a more liquid substance after digestion which decreases ammonia emission but with a higher TAN content increasing ammonia emission (Amon *et al.*, 2006). Overall, the emission of ammonia from untreated and digested manures in this study present no considerable changes. In the case of co-digestion ammonia emission was reduced.

Nitrogen utilization and emissions from the field depend very much on local aspects such as soil properties, climate and management. The replacement rates of nitrogen from digestate to mineral fertilizer therefore is uncertain. Specifically when viewing in the long term, nitrogen dynamics can change considerably in the soil (Schröder *et al.*, 2007). Therefore, exact replacement rates are difficult to predict.

Allocation
In this study no allocation was applied since no co-products existed in the system. However, different allocation methods, e.g., based on mass, energy content or economic value, have shown varying results in life cycle assessment studies (Thomassen *et al.*, 2008).

Sustainability
Sustainability can be defined as triple P: people, planet and profit which represents the main areas affected through choices and activities. This study focused on the planet side of sustainability and therefore does not give a full overview of the people and profit side of sustainable production. However, it included more environmental indicators as compared to other studies and therefore shows a broader scope of the environmental impact. Moreover, anaerobic digestion has been reported to be an economical viable method for the production of renewable energy (NIRAS, 2003). This only holds when co-substrates are used since manure in itself does not produce sufficient methane and thus energy.

A recent study concluded that digesting only manure will reduce greenhouse gases more compared to co-digestion (Zwart *et al.*, 2006). This study concludes that co-digestion will reduce greenhouse gases in a greater extent. This is mainly due to different system boundaries and assumptions in both studies. Zwart *et al* (2006) use an assumptions of 95% reduction in methane, nitrous oxide and ammonia emissions from manure storages in the case of digestion. Comparing to this research a reduction of methane of approximately 67% was assumed whereas it was assumed that nitrogen gases were the same when no digestion took place.

Other quality indicators of manure, such as, organic material are not valued in this study. Changes in organic matter content occur during digestion and therefore will affect the carbon sequestration rate in the soil. Depending on circumstances and requirements it might be preferable to use manure instead of, e.g., mineral fertilizers for supplying N, P and K.

Land use
Land use has been considered only for the production of the co-substrate. However, when considering indirect consequences, this land will not be available for the production of other resources, such as, food, feed or other fuel products. This subject has been a focus point of many discussions around the concept of ‘food, feed or fuel’ and should be considered in analysis which focus on the overall impacts of manure co-digestion on larger scale. Such analysis should also include or indicate indirect land use changes which can be considerable depending on the scale of the activity (Fargione *et al.*, 2008). This research focused on farm scale level. Therefore, conclusions of this research can not directly be extrapolated to another level of scale. It is recommended to assess further impacts of these indirect land use affects.

Other co-substrates currently used are by-products from other production processes such as, glycerin resulting from biodiesel production and animal fats resulting from slaughtering. These products offer the potential to produce energy without directly impacting land use and land use change. However, this strongly depends on market circumstances and the alternative use of the by-products. Moreover, the method of calculating the environmental impact related to these co-substrates will determine how co-digestion performs from an environmental point of view (de Vries *et al.*, 2010).

Furthermore, land use can be addressed to the installation for the biogas plant. When compared to the overall land required for the production of co-substrates and indirectly manure, this can be assumed as negligible.

5.2 Conclusions

Considering this study, we can conclude the following:

- Digestion and co-digestion of manure with silage maize led to a potential lower emission of CO_2-eq compared to using untreated manure in this study. Co-digestion of manure and silage maize reduced CO_2-eq emissions most.
- Energy production increased dramatically when co-digestion of manure and silage maize was applied. Furthermore, acidification and eutrophication potentials tended to decrease.
- Co-digestion presents the opportunity to reduce acidification and eutrophication potentials due to a possible lower ammonia emission. Untreated and digested manure did not show a considerable difference in acidification potential although the eutrophication potential tended to decrease.
- Concerning the previous, co-digestion of manure and co-substrates represents the potential to reach the environmental goal of providing renewable energy in a sustainable manner. However, other implications, such as, indirect land use change and long term carbon sequestration, when using digestate, should be considered further for decision making.

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