Life Cycle Inventory & Assessment Report: Cooling of Manure, Applied to Fattening Pigs Slurry, Denmark

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Baltic Forum for Innovative Technologies for Sustainable Manure Management

KNOWLEDGE REPORT

Life Cycle Inventory & Assessment Report: Cooling of Manure, Applied to Fattening Pigs Slurry, Denmark

By Marianne Wesnæs, Lorie Hamelin & Henrik Wenzel

- WP5 Assessing Sustainability of Manure Technology Chains
- December 2013
Baltic Manure WPS Assessing Sustainability of Manure Technology Chains

Life Cycle Inventory & Assessment Report: Cooling of Manure, Applied to Fattening Pigs Slurry, Denmark

By Marianne Wesnæs, Lorie Hamelin & Henrik Wenzel, University of Southern Denmark

2013
Preface

This report presents the inventory data, results and interpretation of a consequential life cycle assessment carried out for the technique “Cooling of manure”, as applied to fattening pigs slurry, in the context of Denmark.

It was produced as part of work package 5 of the project “Baltic Forum for Innovative Technologies for Sustainable Manure Management (Baltic Manure)”. The long-term strategic objective of the Baltic Manure project is to change the general perception of manure from a waste product to a resource, while also identifying its inherent business opportunities with the most suitable manure handling technologies and policy framework, for the Baltic Sea Regions (BSR). Baltic Manure is partly financed by the European Union (European Regional Development Fund), through the Baltic Sea Region Programme 2007-2013.

The report was performed and edited by Marianne Wesnæs and Lorie Hamelin (University of Southern Denmark), and benefited from the advices of Henrik Wenzel (University of Southern Denmark).

Internal review of the inventory analysis part of the LCA was performed by Sirli Pehme, Estonian University of Life Sciences and Andras Baky, Swedish Institute of Agricultural and Environmental Engineering (JTI).

December 2013

The authors
Table of Contents

1 Introduction ........................................................................................................................................... 5
  1.1 Background and objective (overall Baltic Manure project) ................................................................. 5
  1.2 Objective, summary (this LCA report) ............................................................................................... 6
  1.3 Organization & Participants ............................................................................................................ 6

2 Scope ................................................................................................................................................... 7
  2.1 Methodology ..................................................................................................................................... 7
  2.2 Background and objective (this LCA report) .................................................................................. 8
  2.3 Basis for the comparison: The functional unit .............................................................................. 9
  2.4 System Boundaries ....................................................................................................................... 9
    2.4.1 System boundaries for the reference scenario ........................................................................ 10
    2.4.2 System boundaries for the manure cooling scenario ........................................................... 10
  2.5 Temporal, geographical and technological coverage ................................................................... 12
  2.6 Data ................................................................................................................................................ 12
  2.7 Impact categories ........................................................................................................................... 13

3 Life Cycle Inventory data for Reference scenario ........................................................................... 14

4 Life Cycle Inventory data for Manure Cooling ............................................................................... 17
  4.1 Cooling of fattening pig manure in the housing units ................................................................. 17
    4.1.1 NH3 emissions ........................................................................................................................ 17
    4.1.2 CH4 and CO2 emissions ........................................................................................................ 18
    4.1.3 N2O emissions ........................................................................................................................ 20
    4.1.4 Heat pump: Energy consumption and heat production ....................................................... 20
    4.1.5 Ventilation: Reduced energy consumption ......................................................................... 22
    4.1.6 Life cycle inventory data for the process “Manure Cooling in the housing units” ........ 23
    4.1.7 Mass balances for the process “Manure Cooling in the housing units” ............................ 25
  4.2 Outdoor storage ............................................................................................................................. 25
    4.2.1 CH4 and CO2 emissions ........................................................................................................ 26
    4.2.2 N2O emissions ........................................................................................................................ 28
    4.2.3 Life cycle inventory data for the process “Outdoor storage” ............................................. 29
    4.2.4 Mass balances for the process “Outdoor storage” ............................................................. 30
  4.3 Application to field ......................................................................................................................... 30
    4.3.1 Danish Fertiliser Legislation ................................................................................................. 30
    4.3.2 Fertilizer substitution .......................................................................................................... 31
    4.3.3 Increased Yield ...................................................................................................................... 32
    4.3.4 Phosphorous and Nitrate leaching ....................................................................................... 34
    4.3.5 Fate of Carbon in manures applied to soil, CO2 and CH4 emissions ................................ 34
    4.3.6 Life cycle inventory data for the process “Application to field” ....................................... 36
5 Life Cycle Assessment Results and Interpretation .......................................................... 37

5.1 Life cycle Assessment Results including sensitivity analyses .................................. 37

5.2 Discussion .................................................................................................................. 39

5.2.1 Global Warming .................................................................................................. 39

5.2.2 Acidification ....................................................................................................... 40

5.2.3 Aquatic eutrophication, Nitrogen ...................................................................... 40

5.2.4 Aquatic eutrophication, Phosphorous ............................................................... 41

5.3 Conclusion ................................................................................................................ 42

6 References ................................................................................................................... 44
1 Introduction

1.1 Background and objective (overall Baltic Manure project)

In 2009, the European Union Strategy for the Baltic Sea Region (EUSBSR), along with its Action Plan, was approved by the European Council, making it the first macro regional strategy in Europe. As part of the Action Plan, the Strategy promotes Flagships Projects which fall within the scope of the overall objectives of the Strategy, namely: “Save the Sea”, “Connect the Region” and “Increase Prosperity”.

Baltic Manure, which involves 18 partners from 8 BSR countries (Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Poland and Sweden), is one of these Flagship projects. The long-term strategic objective of the Baltic Manure project is to change the general perception of manure from a waste product to a resource, while also identifying its inherent business opportunities with the most suitable manure handling technologies and policy framework.

The project is divided into 7 work packages:

- WP1: Project management and administration
- WP2: Communication
- WP3: Innovative technologies for manure handling
- WP4: Standardisation of manure types with focus on phosphorus
- WP5: Assessing sustainability of manure technology chains
- WP6: Energy potentials of manure
- WP7: Business innovation

The results presented in this document are the outcome of WP5. The objectives of WP5 are two-fold:

- To assess the environmental consequences of different manure management technology chains of relevance for the BSR in order to provide a support for prioritization of these technologies in the different BSR countries:
- To propose a common platform for Life Cycle Assessment (LCA) of manure management in the BSR.

One key outcome expected from WP5 consists of the production of Life Cycle Inventory reports for selected manure processing technology chains that can be used as a support for policy instruments. As a result, a series of such reports were made for a selection of different combinations of manure processing technologies, manure types and BSR countries. An overview of the combinations assessed is available in the final WP5 report.
1.2 **Objective, summary (this LCA report)**

This report presents the inventory data, results and interpretation of the life cycle assessment carried out for the technique “Cooling of manure”, as applied to fattening pigs slurry, for the BSR country Denmark.

It aims to highlight, in a so-called “whole-system perspective”, the environmental consequences of using this manure management technology, as compared to the status-quo (or reference) manure management situation, where the manure is simply stored (in-house and outdoor) and then applied to soil as an organic fertilizer.

1.3 **Organization & Participants**

Baltic Manure is partly financed by the European Union (European Regional Development Fund), through the Baltic Sea Region Programme 2007-2013. The project is led by MTT - Agrifood Research (Finland), with a total budget of 3.7 million €. This 3 year project started in 2011 and ended in 2013.

The participants of WP5 include:
- Juha Grönroos, Katri Rankinen & José E. Cano-Bernal; Finnish Environment Institute (SYKE)
- Lorie Hamelin, Henrik Wenzel, Marianne Wesnæs & Henrik Saxe; University of Southern Denmark
- Andras Baky; Swedish Institute of Agricultural and Environmental Engineering (JTI)
- Sirli Pehme; Estonian University of Life Sciences
- Laura Alakukku & Lauri Larvus; University of Helsinki
- Ksawery Kuligowski, Dorota Skura, Marek Ziółkowski & Andrzej Tonderski; Pomeranian Centre for Environmental Research and Technology (POMCERT)

More details about the Baltic Manure project and the overall participants can be found on the project website; balticmanure.eu.
2 Scope

2.1 Methodology

This report is based on the Life Cycle Assessments method (LCA) described in the Danish EDIP method by Wenzel et al. (1997) and further updates of this method (Hauschild & Potting (2005), Weidema et al. (2004), Weidema (2004), Stranddorf et al. (2005)).

The method used is based on the consequential LCA approach. The purpose of the consequential LCA approach is to show the environmental consequences of the decision that is assessed by the LCA. The LCA shall reflect that choosing one alternative over another involve an increasing demand for that alternative and the environmental consequences of this choice; in this case the consequences of choosing Manure Cooling in the housing units as a replacement for the conventional slurry management methods in Denmark. This is done through system expansion and the use of marginal data, striving to include only what is affected by a change in demand for the alternative technology.

The consequential approach requires that the LCA is comparative, i.e. that alternatives are compared. The consequential and comparative approach ensures that all compared alternatives are equivalent and provide the same services to society, not just regarding the primary service, which is the “main function” of the system (which is in this study “management of manure from fattening pigs”), but also on all secondary services. Secondary services are defined as products/services arising e.g. as co-products from processes in the studied systems. In this study, secondary functions are for example the nutrient value of the slurry (that can replace mineral fertilisers) or the energy produced by the heat pump for the manure cooling (replacing other heat production). See further explanation of comparative and consequential LCA in Hamelin (2013), Wenzel (1998), Ekvall and Weidema (2004) and Weidema (2004).

In this LCA, biogenic CO$_2$ is included. It would not be correct to regard manure as “CO$_2$ neutral”. Consequential LCAs are always based on comparisons, and in order to make the comparison reasonable, the compared systems are based on the same “starting point” (i.e. the functional unit; in this case 1000 kg pig slurry ex-animal). The composition of the pig slurry ex-animal is also identical in the compared systems; accordingly, both LCAs start with the same amount of carbon (C). The fate of this C is followed throughout the systems, keeping track of the C balances in each step of the life cycle in order to identify the amount ending as CH$_4$, CO$_2$ or in the soil (carbon sequestration). The amount of CO$_2$ will differ between the compared systems, and as biogenic CO$_2$ molecules have the same global warming potential as fossil CO$_2$ molecules, it should be included. Including biogenic CO$_2$ is the only way to demonstrate the benefits of a slurry management technology that leads to increased carbon sequestration.
The carbon in the manure comes from the feed (i.e. the portion of C that was not absorbed by the animals, but excreted). Hence, this “CO₂ uptake” by the growing crops for feed production could have been included in the LCAs and subtracted from the systems; however, as the initial amount of C is the same in all scenarios, it will just blur the conclusions. Furthermore, implementing alternative manure management does not influence the feeding of the animals, and thus, feed production is not included.

2.2 Background and objective (this LCA report)

In 2009, manure cooling was installed on more than 300 pig farms in Denmark, and in 2011, this was increased to approximately 550 pig farms (Hansen et al. (2013) (Appendix 1), Landbrugsinfo (2009) and Danish Environmental Protection Agency (2011)). The growing interest for the manure cooling technology is mainly based on relatively low costs (depending on the utilization of the heat), the opportunities for obtaining heat at low costs, combined with a sturdy and robust technology with a relatively long life time (>15 years) and low demands on maintenance (Landbrugsinfo, 2009 and Danish Environmental Protection Agency, 2011) in addition to reductions of ammonia. The technology is registered as BAT technology (Best Available Techniques) on the Danish list of BAT technologies (Danish Environmental Protection Agency, 2011).

The Manure Cooling Technology reduces ammonia emissions in the housing units, which leads to a higher N content in the manure. The technology is based on a heat pump, which requires electricity; however, it also produces heat that can replace other sources of heat for e.g. heating the housing units for the pigs. The heat produced by the heat pump is typically 3 times the amount of electricity. The environmental consequences of the technology are not straightforward: What are the environmental advantages and disadvantages of the Manure Cooling Technology? The environmental impacts has to be seen in the “manure chain” from in-house storage, outdoor storage and to field application in combination with the environmental impacts from the energy production for the manure cooling. The environmental consequences have not been assessed in this perspective before.

Thus, it is relevant to investigate if this technology is an environmental improvement compared to the conventional slurry handling for fattening pig manure. The question is, if it can be recommended to install Manure Cooling for slurry from fattening pigs (instead of “the conventional slurry handling”) from an environmental point of view.

Accordingly, the goal of this life cycle assessment is to identify the environmental consequences of introducing the technology “Manure Cooling” in the housing units for fattening pigs in Denmark compared to the reference management procedures for fattening pig slurry (“business-as-usual” in Denmark today).
2.3 Basis for the comparison: The functional unit

In order to make a reasonable comparison it is fundamental to perform the LCA in relation to the same function, i.e. the same service i.e. “the Functional Unit”. The Cooling Manure scenario has been compared to the reference scenario based on the functional unit “1000 kg slurry “ex-animal”, i.e. right after excretion. The composition of the reference slurry is shown in table 3.1 in section 3 below.

2.4 System Boundaries

In principle, an LCA covers all environmental impacts from all processes in the entire chain; however, when comparing alternatives, it is not necessary to include processes that are identical in the compared systems. In this study, focus has been put on the differences between the scenarios, and the processes, that are identical for the reference scenarios and the alternative technologies have been left out. Common for all the scenarios in this study are all the processes “upstream” of the slurry excretion, i.e. production of pigs, production of feed, medicine, hormones, housing systems etc. In other words, the system starts when the slurry leaves the pig and hits the floor or the slurry pits in the housing system.

Gaseous emissions (e.g. CH₄ through enteric fermentation or CO₂ through respiration) from the animals are not included within the system boundaries, as changed slurry management has no influence on the enteric fermentation and on the respiration. It is not claimed that the processes “upstream” (i.e. before the slurry excretion) have no environmental significance - it is just outside the frame of this study.

Included within the system boundaries are all processes related to slurry handling: e.g. slurry storage (in-house, pre-tank, outdoor storage), slurry treatment, electricity needed for slurry handling (pumping, stirring, transport needed and fertilisation operations, slurry application and slurry fate in the soil).

A reference crop rotation has been established in order to estimate the ammonia emissions in the period after application in the field. However, the life cycle of these crops is not included within the system boundary (e.g. sowing and harvesting operations, tillage, management of the crop residues, etc.), as this is not a consequence of the slurry management. In the Manure Cooling scenario, however, the crop yield is affected, and the system has been expanded in order to reflect the consequences of an increased yield (more about this in section 4.3.3).
2.4.1 System boundaries for the reference scenario

The reference scenario used in this study reflects the conventional manure management practices for fattening pig manure in Denmark. The reference scenario can be summarised as the following three main stages: in-house storage, outdoor storage and application to field.

Once excreted, the pig manure is stored in-house in the slurry pit below the animals. On a regular basis, the pits are emptied and the slurry is temporarily transferred to an outdoor pre-tank. From the pre-tank, the slurry is transferred to an outdoor covered storage tank, made of concrete. The cover consists of a cut straw cover. Slurry will remain in the storage tank until the suitable period for field fertilisation. When suitable, the slurry will be pumped from the storage tank, transported to the field and applied to the fields as fertiliser. See figure 2.1.

Figure 2.1: System Boundaries for the reference system

2.4.2 System boundaries for the manure cooling scenario

The Manure Cooling Scenario includes cooling of manure from fattening pigs. The manure cooling takes place in the housing units. The purpose of manure cooling is to reduce NH₃ emissions. NH₃ volatilization from manure is dependent on the temperature of the manure; accordingly, cooling of the manure reduces the ammonia evaporation. Manure cooling also reduces CH₄ and CO₂ emissions as cooling reduce the growth of methanogenic bacteria (Hilhorst et al., 2001).

Manure cooling of pig manure can be installed either under the manure canals (in new buildings) or above the concrete via cooling pipes in the bottom of the canals. The cooling pipes are connected to a heat pump, and the recovered heat from this can be used for heating purposes (for example in the housing units for weaning pigs or farrowing sows). In Denmark, however, it will normally not be possible to utilize the heat in the housing units for fattening pigs, except for short periods during winter months (Hansen et al., 2012). Manure cooling is mainly interesting for pigs
on partly slatted floor, as fully slatted floors might become too cold for the pigs (welfare) (Pedersen, 1997).

As the ammonia volatilization is reduced, the slurry has a higher content of N ex-housing units. Accordingly, an increase in ammonia emissions during outdoor storage and during application is expected, and furthermore, there is a risk of increased leaching of nitrate at the field, compared to the reference system.

Furthermore, the higher content of N ex-housing units might lead to increased yield at the fields, if the farmer spreads the same amount of manure per hectare as he would without slurry cooling (i.e. compared to the reference system).

The system boundaries for the Manure Cooling scenario are shown in figure 2.2.

*Figure 2.2: System Boundaries for the scenario “Manure Cooling”. Dotted lines indicate avoided processes.*
2.5 Temporal, geographical and technological coverage

The study has been based on data from the most recent year for which consistent data are available. The Reference manure composition for Denmark is based on year 2011. It is the intention that data used for this study should apply for 2011 and following 5-7 years. The scenario in this report covers manure management under Danish conditions (e.g. housing systems, storage facilities, soil types, application methods, energy production and legislation regarding fertilisation and nutrient substitution). As the slurry composition varies significantly within the European countries due to differences in on-farm management, e.g. for feeding, it is not possible to transfer the results of this study directly to other European countries without adjustments.

For the reference scenario, the technological coverage is based on “average technology” and represents the “state of the year 2011”. The intended technology level for the Manure Cooling Scenario is “Modern Technology” i.e. technology existing today and that will most likely be the technology use during the upcoming years. In cases, where a range of data for emissions and the performance have been collected for a technology, the highest end-of-the-interval has been chosen as a best representation of “modern & future” technologies to be implemented.

2.6 Data

Data for the reference system and manure composition is based on Danish-specific data for manure management in accordance with the recommendations by the Ministry of Food, Agriculture and Fisheries of Denmark, The Danish AgriFish Agency (Poulsen et al., 2011 and Ministry of Food, Agriculture and Fisheries of Denmark, 2012), and emission factors for ammonia is also based on this.

Emission factors for methane and nitrous oxide are based on the IPCC Guidelines for National Greenhouse Gas Inventories from the Intergovernmental Panel on Climate Change (IPCC, 2006). Emission factors for nitrogen monoxide and nitrogen is based on “EMEP/EEA air pollutant emission inventory guidebook 2009 - Technical guidance to prepare national emission inventories” from the European Environment Agency (and the 2010 update of this). When needed, these factors have been combined with data from various literatures; see the references at the end of the report.

Data for the manure cooling technique is based on information from the Danish Environmental Protection Agency combined with Danish literature. Data on energy systems, energy production and the technology used in the agricultural production systems is based on a combination of Danish-specific data and the Ecoinvent v.2.2 database (Ecoinvent, 2007 and the Ecoinvent report for data on agricultural production systems: Nemecek, 2007).
The Life Cycle Assessment was facilitated with the LCA software SimaPro 7.3.3.

2.7 Impact categories

Four main impact categories are included: Global warming, acidification and nutrient enrichment (distinguishing between N and P being the limiting nutrient for growth), these being seen as the most relevant for agricultural biomass systems (see further explanation in the Main Report by Hamelin et al. (2013a)).
3  **Life Cycle Inventory data for Reference scenario**

The Life Cycle Inventory data for the reference scenario is described in Hamelin et al. (2013b). This section contains a summary only.

The main preconditions for the reference system for fattening pigs, Denmark are:
- A housing system with “partly slatted floor with 25-49% solid floor”
- From the pre-tank in connection with the housing units the slurry is pumped to the outdoor storage in concrete slurry tanks and covered by a floating layer (straw)
- The transport distance from storage to application to fields has been estimated to 10 km.
- The slurry is applied with trail hose tankers to the field.
- The Danish soil type JB3 has been used representing sandy soil (and clay soils not considered).
- It is assumed that the slurry is applied to all crops in the crop rotation pattern (six year rotation).

The manure composition data are given in table 3.1 below. A detailed description of the algorithms and assumptions behind the manure composition and mass balances are given in Hamelin et al. (2013b).

Life Cycle Inventory data for the reference system is shown in table 3.2. A detailed description of the algorithms and assumptions for these are given in Hamelin et al. (2013b).
The project is partly financed by the European Union - European Regional Development Fund

Table 3.1. Manure composition for the reference system (fattening pig slurry, Denmark). All data per 1000 kg slurry (at the respective manure stage, i.e. ex-animal, ex-housing or ex-outdoor storage)

<table>
<thead>
<tr>
<th>Manure stage</th>
<th>Manure stage ex-animal</th>
<th>ex-housing</th>
<th>ex-outdoor storage</th>
<th>Comments ex-animal</th>
<th>ex-housing</th>
<th>ex-outdoor storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mass (ton)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>Mass balance a</td>
<td>Mass balance a</td>
<td></td>
</tr>
<tr>
<td>Dry matter (DM) (kg)</td>
<td>74.52</td>
<td>68.57</td>
<td>66</td>
<td>Mass balance c</td>
<td>Mass balance c</td>
<td>Poulsen (2011)</td>
</tr>
<tr>
<td>Ash content (kg)</td>
<td>14.15</td>
<td>14.13</td>
<td>13.86</td>
<td>DM minus VS</td>
<td>DM minus VS</td>
<td></td>
</tr>
<tr>
<td>Volatile solids (VS) (kg)</td>
<td>60.36</td>
<td>54.44</td>
<td>52.1</td>
<td>Same loss, in absolute, as DM</td>
<td>Same loss, in absolute, as DM</td>
<td>Based on an average of Danish data, VS is 79% of TS for fattening pig slurry) C:DM ratio is 18.2/38 for pig slurry (Knudsen and Birkmose, 2005)</td>
</tr>
<tr>
<td>Carbon (C) (kg)</td>
<td>33.55</td>
<td>33.5</td>
<td>31.6</td>
<td>Mass balance d</td>
<td>Mass balance d</td>
<td></td>
</tr>
<tr>
<td>Total N (kg)</td>
<td>6.00</td>
<td>5.262</td>
<td>5.045</td>
<td>Poulsen, 2011</td>
<td>Mass balance e</td>
<td>Mass balance e</td>
</tr>
<tr>
<td>Phosphorus (P) (kg)</td>
<td>1.21</td>
<td>1.21</td>
<td>1.19</td>
<td>Poulsen, 2011</td>
<td>Mass balance f</td>
<td>Mass balance f</td>
</tr>
<tr>
<td>Potassium (K) (kg)</td>
<td>2.83</td>
<td>2.85</td>
<td>2.826</td>
<td>Poulsen, 2011</td>
<td>Mass balance g</td>
<td>Mass balance g</td>
</tr>
<tr>
<td>Copper (Cu) (kg)</td>
<td>0.0310</td>
<td>0.03097</td>
<td>0.0304</td>
<td>Mass balance h</td>
<td>Mass balance h</td>
<td>Cu:DM ratio is 0.0175/38 for pig slurry (Knudsen and Birkmose, 2005)</td>
</tr>
<tr>
<td>Zinc (Zn) (kg)</td>
<td>0.0908</td>
<td>0.0907</td>
<td>0.0891</td>
<td>Mass balance i</td>
<td>Mass balance i</td>
<td>Zn:DM ratio is 0.0513/64 for pig slurry (Knudsen and Birkmose, 2005)</td>
</tr>
</tbody>
</table>

Details described in Hamelin et al. (2013b).

- a Change in total mass during in-house storage: +1.934 kg added straw + 7.598 kg added water minus change in DM.
- b Change in total mass during outdoor storage: +2.5 kg added straw + 20.383 kg added water minus change in DM.
- c Change in DM: + DM added by straw minus DM losses. DM in straw: 850 kg DM/ton straw (Møller et al., 2000). DM losses: Danish losses are 10% in the housing units and 5% during outdoor storage (Poulsen, 2008).
- d Change in Total-C: C from added straw (same amount as in reference system minus emissions of CO2-C and CH4-C). 0.4563 kg C/kg DM (Mean value from Biolex database) (www.biolexbase.dk)
- e Change in Total-N: N from straw (same as reference system) minus emissions of NH3-N, NO2-N, NO-N and N2-N (indirect emissions of N2-O-N not included). N added by straw: 0.00528 kg N/kg dm: Møller et al. (2000)
- f P from added straw as in reference system. 0.0009 kg P/kg dm: Møller et al. (2000)
- g K from added straw as in reference system. 0.015 kg K/kg dm: Møller et al. (2000)
- h Cu from added straw as in reference system. 3 mg Cu/kg dm: Møller et al. 2000
- i Zn from added straw as in reference system. 46 mg Zn/kg dm: Møller et al. 2000
Table 3.2 Life Cycle Inventory data for the reference system, fattening pig slurry, Denmark

<table>
<thead>
<tr>
<th>Emissions</th>
<th>In-house storage (kg per 1000 kg manure)</th>
<th>Outdoor storage (kg per 1000 kg manure)</th>
<th>Field (kg per 1000 kg manure)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH₃-N</td>
<td>0.71</td>
<td>0.099</td>
<td>0.605</td>
<td>0.17 kg NH₃-N per kg TAN&lt;sup&gt;ex-animal&lt;/sup&gt; (Poulsen et al., 2008, table 8.3) with 0.7 kg TAN/kg N (EMEP/EEA, 2010, table 3-8). 2.5% of TAN&lt;sup&gt;ex-housing&lt;/sup&gt; (Poulsen et al., 2008, table 9.7); the N ex-housing being estimated according to Poulsen et al. (2008), i.e., N ex-animal minus NH₃-N losses in-house (not accounting other losses). 12% of N applied (Hansen et al., 2008) (this is an average for application by trail hose tanker, excluding illegal dates)</td>
</tr>
<tr>
<td>NH₃-N, at application</td>
<td>-</td>
<td>-</td>
<td>0.015</td>
<td>0.005 kg N₂O-N per kg N&lt;sup&gt;ex-animal&lt;/sup&gt; (IPCC, 2006), distributed 30% to in-housing and 70% to outdoor storage, see explanation in Hamelin et al. (2013b)</td>
</tr>
<tr>
<td>N₂O-N</td>
<td>0.0090</td>
<td>0.02096</td>
<td>0.050</td>
<td>0.0001 kg NO per kg TAN&lt;sup&gt;ex-animal&lt;/sup&gt; (EMEP-EEA (2010), Table 3.9) 0.0001 kg NO per kg TAN&lt;sup&gt;ex-housing&lt;/sup&gt; (EMEP-EEA (2010), Table 3.9) 0.1×N₂O-N, based on (Nemecek and Kägi, 2007)</td>
</tr>
<tr>
<td>NO-N (representing NO&lt;sub&gt;x&lt;/sub&gt;)</td>
<td>1.96×10&lt;sup&gt;-4&lt;/sup&gt;</td>
<td>1.84×10&lt;sup&gt;-4&lt;/sup&gt;</td>
<td>0.0050</td>
<td>1.83 kg CO₂ per kg CH₄&lt;sup&gt;(1) &lt;/sup&gt; (Hamelin et al., 2014, section 5) 1.83 kg CO₂ per kg CH₄&lt;sup&gt;(2) &lt;/sup&gt; (Hamelin et al., 2014, section 5) Based on Danish NLES model (Kristensen et al., 2008)</td>
</tr>
<tr>
<td>NO&lt;sub&gt;3&lt;/sub&gt;-N</td>
<td>0</td>
<td>0</td>
<td>2.29</td>
<td>Assumption: No leaching, as leakages from animal housing units are prohibited in Denmark</td>
</tr>
<tr>
<td>N₂-N</td>
<td>0.0126</td>
<td>0.0118</td>
<td>0.003</td>
<td>0.003 kg NO per kg TAN&lt;sup&gt;ex-animal&lt;/sup&gt; (EMEP-EEA (2009), Table 3.9) 0.003 kg NO per kg TAN&lt;sup&gt;ex-housing&lt;/sup&gt; (EMEP-EEA (2009), Table 3.9) Not included as it is not needed for the mass balanced</td>
</tr>
<tr>
<td>CO₂-C (CO&lt;sub&gt;2&lt;/sub&gt;)</td>
<td>0.298 (1.09)</td>
<td>0.893 (3.274)</td>
<td>30.0</td>
<td>1.83 kg CO₂ per kg CH₄&lt;sup&gt;(3) &lt;/sup&gt; (Hamelin et al., 2014, section 5) 1.83 kg CO₂ per kg CH₄&lt;sup&gt;(4) &lt;/sup&gt; (Hamelin et al., 2014, section 5) Based on Danish C-TOOL model, see section 4.3.5</td>
</tr>
<tr>
<td>CH₄-C (CH₄)</td>
<td>0.448 (0.598)</td>
<td>1.342 (1.789)</td>
<td>0</td>
<td>IPCC (2006) algorithm, distributed 25% to in-house storage and 75% to outdoor storage, see explanation in Hamelin et al. (2013b) Assumed negligible for aerobic conditions.</td>
</tr>
<tr>
<td>P leaching</td>
<td>0</td>
<td>0</td>
<td>0.0324 (0.00727)</td>
<td>Assumption: No leaching, as leakages from animal housing units are prohibited in Denmark</td>
</tr>
<tr>
<td>Indirect N₂O-N (due to emissions of NH₃ and NO&lt;sub&gt;x&lt;/sub&gt;)</td>
<td>0.00714</td>
<td>0.000991</td>
<td>0.0061</td>
<td>0.01 kg N₂O-N per kg (NH&lt;sub&gt;₃&lt;/sub&gt;-N + NO₃⁻-N) (ex-animal) (IPCC (2006b) table 11.3) 0.01 kg N₂O-N per kg (NH&lt;sub&gt;₃&lt;/sub&gt;-N + NO₃⁻-N) (ex-housing) (IPCC (2006b) table 11.3) 0.01 kg N₂O-N per kg (NH&lt;sub&gt;₃&lt;/sub&gt;-N + NO₃⁻-N) (ex-storage) (IPCC (2006b) table 11.3)</td>
</tr>
<tr>
<td>Indirect N₂O-N (due to NO₃ leaching)</td>
<td>0</td>
<td>0</td>
<td>0.0172</td>
<td>No leaching, see above</td>
</tr>
</tbody>
</table>

<sup>ex-animal</sup> Ammonium-N (NH₄⁻-N) and compounds readily broken down to NH₄⁻-N are referred to as total ammoniacal N (TAN)
4 Life Cycle Inventory data for Manure Cooling

The life cycle inventory for the Manure Cooling scenario is to a great extent a modification of the reference scenario for fattening pig manure, Denmark.

The starting point for all the mass balances and calculations of emissions are the manure composition ex-animal (i.e. as excreted), which is identical to the manure composition ex-animal for the reference scenario. The manure composition ex-animal is the only thing that is the same in all the LCAs; this is a precondition for the comparison. The manure composition ex-animal is shown in table 3.1, the first column in section 3.

4.1 Cooling of fattening pig manure in the housing units

4.1.1 $NH_3$ emissions

In Danish tests in housing units for fattening pigs on fully slatted floors, the ammonia emissions was reduced with 10 % for every 10 W/m$^2$ cooling effect applied (Pedersen, 1997). Pedersen (1997) recommends a maximum cooling of 20 W/m$^2$ on fully slatted floors to prevent the floors to become too cold for the fattening pigs, but adds that the cooling effect might be increased under partly slatted floors. As the reference system in this study is partly slatted floors (25-49% solid floor), and as this also applies for this Manure Cooling scenario, the cooling effect has not been limited to the 20 W/m$^2$.

Danish tests with cooling of slurry in housing units for sows in gestation pens show ammonia reductions of 31% with an average cooling effect of 24 W/m$^2$ (Pedersen, 2005). According to BAT (Best Available Techniques) guidelines by the Danish Environmental Protection Agency (2011) and Hansen et al. (2012), the reduction of ammonia in % can be calculated as a function of the cooling effect, using the algorithms below:

\begin{align*}
(1)\quad & \text{For housing units with frequent slurry removal e.g. with mechanical removal:} \\
& NH_3 \text{ reduction (\%)} = -0.008 x^2 + 1.5 x \\
(2)\quad & \text{For traditional slurry system with 40 cm deep slurry canals:} \\
& NH_3 \text{ reduction (\%)} = -0.004x^2 + x \\
& x = \text{cooling effect (in W/m}^2) \\
\end{align*}

The upper limit for the cooling effect is not stated.
The results of recent tests have shown a reduction of the ammonia emissions at 51% with an average cooling effect of 55 W/m² when applying slurry cooling under slatted floor in the resting area (Jørgensen et al., 2013).

For the Manure Cooling scenario in this study, a reduction of the NH₃ emissions of 51% (compared to the reference scenario) has been applied, as this is regarded the optimized and realistic future technology for manure cooling (based on the Danish tests described in Jørgensen et al., 2013).

Furthermore, a sensitivity analysis has been carried out, based on the BAT guidelines by the Danish Environmental Protection Agency (2011) (equation 2 describe in the text above), using the maximum cooling effect mentioned, i.e. 30 W/m² (the upper limit for cooling effect is not given). This corresponds to a NH₃ reduction of 26.4%, when applying the algorithm for “Traditional slurry system with 40 cm deep slurry canals”.

### 4.1.2 CH₄ and CO₂ emissions

Hansen et al. (2012) found a couple of references indicating that the cooling of slurry reduces the methane emissions. Hilhorst et al. (2001) describes the theoretical background for how cooling affects the growth rate of different type of methanogenic bacteria. Hilhorst et al. (2001) refers to and experiment from 1996 on a Dutch pigfarm, where the measured emission reduction for CH₄ as well as for NH₃ was between 30 to 50% (These information is based on Hilhorst et al. (2001) and not the original reference (Groenestein, C.M. & J.H.W. Huis in 't Veld, 1996) as the original reference is in Dutch).

A recent comprehensive Danish study on Biogas potentials of manure and effects of pre-treatment (based on measurements on a large amount of manure) concludes “Before manure is subjected to digestion it is stored for shorter or longer period inside the live-stock buildings, which can result in losses of methane. The influence of storage temperature and time has been tested. In the experiment especially the loss from manure from fattening pigs has been very high. During summertime with temperature around 20°C the loss can be around 1% per day and since manure often is stored 15-30 days in the stable and in collection tanks this means that manure can lose up to 50% of the methane potential... Losses can be reduced considerably in pig manure by slurry cooling or acidification” (Møller, 2013). Based on the measurements, a biogas potential for fattening pig slurry at 220-350 litre CH₄ per kg VS was found, however, it is emphasized that the manure samples was taken in June after the manure had been stored in the housing units for 14-30 days, which is normal practice in Denmark (Møller, 2010). When comparing this biogas potential to the methane loss from storage in figure 4.1 (identical to figure 3 in Møller (2013)), it can be seen that after 14 days, a significant amount of biogas potential can be lost if fattening pig

\[ \text{NH₃ reduction (\%)} = -0.004x^2 + x, \text{ where } x = \text{cooling effect: } 30 \text{ W/m}^2, \text{ which gives a NH₃ reduction of 26.4\%} \]
manure is stored at 20°C. Please note that the scale on the axis with “L CH₄/kg VS” is NOT identical at the 10°C, 15°C and 20°C graph.

Figure 4.1. Loss of methane potential during storage of manure before digestion in a biogas plant. Please note that the scale on the axis with “L CH₄/kg VS” is NOT identical at the 10°C, 15°C and 20°C graph. Copied from figure 3 in Møller (2013).
Rough estimates based on calculations from figure 4.1 indicates that for fattening pig manure stored for 28 days at 20°C, cooling to 15°C might reduce the methane emissions by around 30%, and cooling to 10°C a reduction of around 77%. If the fattening pig manure is stored for 15 days, cooling to 15°C might reduce the methane emissions by 31% and cooling to 10°C might give a reduction by 78%. The reductions are very rough estimates; however, they verify that a reduction level at 30-50% as indicated by Hilhorst et al. (2001) is not unrealistic.

For the “Manure Cooling scenario” in this study, it is assumed that the CH$_4$ emissions are at the same level as the NH$_3$ reductions, i.e. 51% (compared to the reference scenario). The uncertainty on the CH$_4$ reductions is considerable. Furthermore, it is assumed, that the reduction of the CO$_2$ emissions is at the same level as the CH$_4$ reduction, i.e. 51% of the reference scenario (as the CO$_2$ and CH$_4$ emissions are interrelated, see the description CO$_2$-CH$_4$ ratio calculations in Hamlin (2013)).

In addition, the sensitivity analysis described in section 4.1.1 includes a reduction of the CH$_4$ and CO$_2$ emissions, assuming the same reduction level as for the NH$_3$ reductions, i.e. a reduction of 26.4%.

### 4.1.3  N$_2$O emissions

The N$_2$O emissions might change when cooling manure, however, Dustin (2002) cites two references, which observed that apparently, there were no relationship between temperature and N$_2$O emissions during storage. Accordingly, it is assumed that the N$_2$O emissions are not affected by cooling (when comparing to the reference scenario).

### 4.1.4  Heat pump: Energy consumption and heat production

The electricity consumption for the heat pump and the amount of heat produced depends on the applied cooling effect. The cooling effect is typically two times the electricity consumption by the heat pump (i.e. use of 1 kW electricity will induce a cooling effect of 2 kW), and heat produced by the heat pump is typically 3 times the amount of electricity (Danish Environmental Protection Agency (2009) and (2011)). Examples of cooling effect, electricity consumption and produced heat are given in table 4.1, together with the reductions in NH$_3$ emissions.

---

3 Section ”S CO2: CH4 ratio and calculation of methane potential” in in Hamelin et al. (2014), Appendix D: Supporting Information for: Environmental Consequences of Different carbon Alternatives for Increased Manure-Based Biogas, page s60-s61.
**Table 4.1 Cooling effect, electricity consumption and NH3 reductions for manure cooling, fattening pigs.**

<table>
<thead>
<tr>
<th>Cooling effect [kWh/m²]</th>
<th>Electricity consumption [kWh per ton manure ex-animal]</th>
<th>Heat produced [kWh per ton manure ex-animal]</th>
<th>NH3 reduction [%]</th>
<th>Reference and comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 W/m²</td>
<td>10.9 kWh</td>
<td>32.6 kWh</td>
<td>9.6%</td>
<td>Hansen et al. (2012), table 12, page 22 and table 2, page 6 and BAT-sheet, Danish Environmental Protection Agency (2011).</td>
</tr>
<tr>
<td>20 W/m²</td>
<td>21.8 kWh</td>
<td>65.2 kWh</td>
<td>18.4%</td>
<td>Hansen et al. (2012), table 12, page 22 and table 2, page 6 and BAT-sheet, Danish Environmental Protection Agency (2011).</td>
</tr>
<tr>
<td>24 W/m²</td>
<td>-</td>
<td>-</td>
<td>31%</td>
<td>Applies for sows. BAT-sheet, Danish Environmental Protection Agency (2011).</td>
</tr>
<tr>
<td>30 W/m²</td>
<td>32.6 kWh</td>
<td>97.9 kWh</td>
<td>26.4%</td>
<td>Hansen et al. (2012), table 12, page 22 and table 2, page 6 and BAT-sheet, Danish Environmental Protection Agency (2011).</td>
</tr>
<tr>
<td>55 W/m²</td>
<td>60 kWh</td>
<td>180 kWh</td>
<td>51%</td>
<td>Based on tests. Jørgensen et al., (2013). 51% NH3 reduction based on tests.</td>
</tr>
<tr>
<td>Not stated</td>
<td>11.2 kWh</td>
<td>33.6 kWh</td>
<td>Not stated</td>
<td>Takala (2013) from Pellon Group Oy, Finland. Pig house for 1000 animal places (fattening pigs). Energy produced 8-9 kW (continuous power). Energy needed is 1/3 of energy produced, i.e. to produce 1 kW of energy, 1/3 kW is consumed.</td>
</tr>
</tbody>
</table>

a For a cooling effect of 10 kWh/m², the energy consumption is 184 kWh per DE per year (fattening pigs, 25-49% solid floor) and 36 fattening pigs per DE 0.47 ton slurry e-animal per fattening pig (Poulsen, 2012). Electricity consumption: 184 kWh per DE per year / 36 pigs per DE per year / 0.47 ton slurry per pig = 10.87 kWh per ton slurry

b The heat produced by the heat pump is typically 3 times the amount of electricity (Danish Environmental Protection Agency (2009)) and (2011)).

c For traditional slurry system with 40 cm deep slurry canals: NH3 reduction (%) = −0.004x² + x, where x = cooling effect (in W/m²) (equation no. 2 in section 4.1.1)

d For a cooling effect of 20 kWh/m², the energy consumption is 368 kWh per DE per year (fattening pigs, 25-49% solid floor) and 36 fattening pigs per DE 0.47 ton slurry e-animal per fattening pig (Poulsen, 2012). Electricity consumption: 368 kWh per DE per year / 36 pigs per DE per year / 0.47 ton slurry per pig = 21.75 kWh per ton slurry

e For a cooling effect of 30 kWh/m², the energy consumption is 552 kWh per DE per year (fattening pigs, 25-49% solid floor) and 36 fattening pigs per DE 0.47 ton slurry e-animal per fattening pig (Poulsen, 2012). Electricity consumption: 552 kWh per DE per year / 36 pigs per DE per year / 0.47 ton slurry per pig = 32.62 kWh per ton slurry

f Data: cooling effect is 55 W/m². For fattening pigs on 25-49% solid floor the cooling area should be calculated as 0.47 m² per fattening pig (Danish Environmental Protection Agency, 2009). A Danish fattening pig produces in average on 0.47 m³ slurry per pig (Poulsen, 2012). Assuming that the average fattening pig is in the fattening pig housing units for 13 weeks, the hours per fattening pig is: 13 weeks x 7 days per week x 24 hours per day = 2184 hours. Calculation: 55 W cooling required per m² floor area / 2 W cooling effect per W electricity x 0.47 m² floor area per fattening pig / 0.47 m³ manure per pig x 2184 hours = 60.06 kWh electricity per m³ manure. As the energy consumption and heat produced are rounded numbers, and as the density of the reference pig slurry is 1053 kg per m³, they are almost identical per m³ manure and per 1000 kg manure.

g Calculation of electricity consumption: 1/3 of 8-9 kW = 3 kW, continuous power for one year : 3 kW * 365 days * 24 hours = 26280 kWh per year. 1000 animal places * 2.35 tons manure per animal place per year (without cleaning water, according to J Grönroos, 2013) = 2350 tons manure. 26280 kWh per year / 2350 tons manure per year = 11.2 kWh electricity per tons manure.
For the Manure Cooling Scenario in this study, the newest test results based on a cooling effect, 55 kWh/m², have been applied. As it can be seen from table 4.1, this results in an electricity consumption of 60 kWh per 1000 kg manure ex-animal, and a heat production of 180 kWh per 1000 kg manure. In order to represent “modern technology” that will be used during the upcoming years (rather than representing “present technology” from the last 5 years) the highest end-of-the-interval has been chosen, as described in section 2.5. This cooling effect corresponds to the maximum reduction of NH₃, CH₄ and CO₂ (51%), as described above.

In Denmark, the produced heat will only be utilized to a limited extend in the housing units for fattening pigs (only for short periods during the winter, if at all, as described in section 2.4.2), and accordingly, it has been assumed that only 20% of the heat is utilized (assuming that the excess heat cannot be used for other purposes).

A sensitivity analysis has been carried out, assuming that all the heat from the heat pump can be used in e.g. the housing units for weaning pigs or for heating the farmer’s private house. This is calculated with the maximum cooling applied (55 W/m²), and 100 % utilisation of the produced heat (180 kWh) per 1000 kg manure and the maximum reduction of NH₃, CH₄ and CO₂ (51%).

It is assumed that the farm is not connected to the district heat grid, as pig farms are normally situated far from cities and the district heat grid. However, it is assumed that the farm is connected to the natural gas grid, and that the marginal heat avoided is produced on the farm (domestic natural gas boiler). The Ecoinvent process “Heat, natural gas, at boiler modulating <100kW/RER/U” has been used for the modelling in SimaPro. The heat produced by natural gas is subtracted from the system, as this production is avoided when utilizing the heat produced by the heat pump.

The electricity production is based on coal, as this is regarded as the “marginal” electricity production in Denmark today. Furthermore, a sensitivity analysis with different assumptions for the marginal electricity production has been carried out, see section 5.1.

4.1.5 Ventilation: Reduced energy consumption

The need for ventilation in the housing units might be reduced, as ammonia emissions are reduced in the housing units, and as the cooling of manure probably also leads to a lower overall temperature in the housing units. However, ventilation is also needed to reduce the humidity, dust, odour and emissions of e.g. hydrogen sulphide in the housing units. Accordingly, there is no direct a relationship between the reduction of NH₃ emissions and need for ventilation.
According to Videncenter for Svineproduktion (The Pig Research Centre of Denmark) (Pedersen, 2011), the requirements for ventilation in pig farms are in Denmark dimensioned on the heat production by the pigs. The ventilation flow in the housing units is typically regulated in accordance with temperature (and for newer plant humidity and CO₂) (Skov, 2013 and Lindgaard, 2012). Thus, it has been assumed, that Manure Cooling does not necessarily lead to reduced ventilation.

However, a sensitivity analysis including reduced ventilation as a consequence of manure cooling has been carried out: According to Pedersen et al. (2010)³, Damsted (2012)⁴ and Riis et al. (2012)⁵, the typical energy consumption for ventilation in the housing units for fattening pigs is in the area of 8.7 kWh m⁻³ manure with a range from 4.6-21 kWh per m⁻³ manure, depending on the age of the technology. A rough estimate for the reduced need for ventilation has been used, assuming that the energy consumption for ventilation is reduced by 50%. Consequently, it is assumed that the reduced need for ventilation corresponds to approximately 4.5 kWh per m⁻³ manure (= 4.5 kWh per 1000 kg manure).

4.1.6 Life cycle inventory data for the process “Manure Cooling in the housing units”

In table 4.2 below, the life inventory data for the process “Cooling of fattening pig manure in the housing units” is shown. As the data for manure cooling is calculated relative to the reference system (see table 3.1 and 3.2). The data in table 4.2 are the data entered in SimaPro.

³ “Normal” energy consumption for ventilation in the housing units for fattening pigs is stated to: 4.1 kWh per fattening pig / pig / 0.47 m³ manure per pig = 8.7 kWh per m³ manure

⁴ 2.9-10 kWh per produced fattening pig (depending on technology level), typical 4 kWh per produced fattening pig / 0.47 m3 manure per fattening pig = 8.5 kWh per m³ manure (range: 6.1-21.3 kWh per m³ manure).

⁵ 8.6-15.2 kWh per animal place / 4 fattening pigs per animal place / 0.47 m³ manure per pig = 4.6-8.1 kWh per m³ manure.
Table 4.2. Life inventory data for “Cooling of fattening pig manure in the housing units”.

<table>
<thead>
<tr>
<th></th>
<th>All emissions per 1 000 kg manure</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manure “ex animal”</td>
<td>1 000 kg</td>
<td>The input to this process is 1 000.0 kg manure “ex-animal”, which is</td>
</tr>
<tr>
<td></td>
<td></td>
<td>also the study’s functional unit. The emissions are calculated relative</td>
</tr>
<tr>
<td></td>
<td></td>
<td>to this.</td>
</tr>
<tr>
<td>Straw</td>
<td>1.9 kg</td>
<td>As reference system.</td>
</tr>
<tr>
<td>Water</td>
<td>7.6 kg</td>
<td>As reference system.</td>
</tr>
<tr>
<td><strong>Output</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manure &quot;ex housing&quot;</td>
<td>1 005.88 kg</td>
<td>Increased due to addition of water and straw, reduced caused by DM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>loss, see table 4.3.</td>
</tr>
<tr>
<td><strong>Energy consumption</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>+1.7 kWh</td>
<td>Electricity for stirring (1.2 kWh) and pumping (0.5 kWh) for transfer of</td>
</tr>
<tr>
<td></td>
<td></td>
<td>slurry from housing units to outdoor storage (as in reference system).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>In SimaPro, this is modelled under “Outdoor storage (consumption of</td>
</tr>
<tr>
<td></td>
<td></td>
<td>resources) together with pumping from the outdoor storage.</td>
</tr>
<tr>
<td></td>
<td>+60 kWh</td>
<td>Electricity consumption for cooling.</td>
</tr>
<tr>
<td></td>
<td>-36 kWh</td>
<td>Avoided heat production. Assumption: 20% of heat produced by the heat</td>
</tr>
<tr>
<td></td>
<td></td>
<td>pump and thereby potentially avoided, i.e. 20% of 180 kWh = 36 kWh. For</td>
</tr>
<tr>
<td></td>
<td>-4.5 kWh</td>
<td>sensitivity analysis: - 180 kWh.</td>
</tr>
<tr>
<td><strong>Emission to air</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>0.146 kg CO2-C i.e. 0.536 kg CO2</td>
<td>49% of reference system (51% reduction compared to reference).</td>
</tr>
<tr>
<td>Methane (CH₄)</td>
<td>0.2196 kg CH4-C i.e. 0.2928 kg CH4</td>
<td>49% of reference system (51% reduction compared to reference).</td>
</tr>
<tr>
<td>Ammonia (NH₃-N)</td>
<td>0.3499 kg NH₃-N</td>
<td>49% of reference system (51% reduction compared to reference).</td>
</tr>
<tr>
<td>Nitrous oxide (N₂O-N),</td>
<td>0.009 kg N₂O-N</td>
<td>Assumed to be identical to reference scenario.</td>
</tr>
<tr>
<td>direct emissions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrous oxide (N₂O-N),</td>
<td>0.0035 kg N₂O-N</td>
<td>Indirect emissions from volatilization, same algorithms as in reference</td>
</tr>
<tr>
<td>indirect emissions</td>
<td></td>
<td>system: 0.010 kg N₂O-N per kg NH₃-N + 0.010 kg N₂O-N per kg NOₓ-N</td>
</tr>
<tr>
<td></td>
<td></td>
<td>volatilized (IPCC, 2006).</td>
</tr>
<tr>
<td>Nitrogen monoxide (NO-N)</td>
<td>0.000196 kg NO-N</td>
<td>Algorithm as in reference system: 0.0001 kg NO per kg TAN (EMEP-EEA</td>
</tr>
<tr>
<td>(representing total NOₓ)</td>
<td></td>
<td>(2010), Table 3.9). As TAN same as reference system, NO-N is the same,</td>
</tr>
<tr>
<td>Nitrogen (N₂-N)</td>
<td>0.0126 kg N₂-N</td>
<td>i.e. 0.000196 kg NO-N</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Algorithms as in reference system: 0.0030 kg N₂ per kg TAN and 0.7 kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TAN per kg N. Based on EMEP-EEA (2009 and 2010), Table 3.9.</td>
</tr>
<tr>
<td><strong>Discharge to water</strong></td>
<td>None</td>
<td>Assumed to be zero, as leakages from housing systems are prohibited in</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Denmark.</td>
</tr>
<tr>
<td><strong>Discharge to soil</strong></td>
<td>None</td>
<td>Assumed to be zero, as leakages from housing systems are prohibited in</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Denmark.</td>
</tr>
</tbody>
</table>

*The number of digits does not reflect the precision, but are only included as the numbers are used for further calculations.*
4.1.7 Mass balances for the process “Manure Cooling in the housing units”

Mass balances for the process “Manure Cooling in the housing units” can be followed in table 4.3.

Table 4.3. Mass balances for the process “Manure Cooling in the housing units”.

<table>
<thead>
<tr>
<th>Manure composition kg per ton manure ex-animal</th>
<th>Mass balance: Change during indoor storage kg</th>
<th>Mass balance: Amount after storage kg</th>
<th>Manure composition kg per ton manure ex-housing j</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mass</td>
<td>+5.88</td>
<td>1005.88</td>
<td>1000</td>
</tr>
<tr>
<td>DM</td>
<td>-2.01</td>
<td>72.51</td>
<td>72.09</td>
</tr>
<tr>
<td>VS</td>
<td>-2.01</td>
<td>58.356</td>
<td>58.015</td>
</tr>
<tr>
<td>Total N</td>
<td>-0.363</td>
<td>5.637</td>
<td>5.604</td>
</tr>
<tr>
<td>Phosphorus (P)</td>
<td>+0.00148</td>
<td>1.21</td>
<td>1.21</td>
</tr>
<tr>
<td>Potassium (K)</td>
<td>+0.0247</td>
<td>2.85</td>
<td>2.84</td>
</tr>
<tr>
<td>Carbon (C)</td>
<td>+0.377</td>
<td>33.92</td>
<td>33.73</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>+0.00000049</td>
<td>0.0310</td>
<td>0.0309</td>
</tr>
<tr>
<td>Zinc (Zn)</td>
<td>+0.000075</td>
<td>0.0909</td>
<td>0.0904</td>
</tr>
</tbody>
</table>

The number of digits does not reflect the precision, but are only included as the numbers are used for further calculations

a Change in total mass: +1.934 kg added straw (as in reference system) + 7.598 kg added water (as in reference system) – Change in DM.
b Change in DM: + DM added by straw (as in the reference system) – DM losses. DM in straw: 850 kg DM/ton straw (Møller et al., 2000). DM losses: Danish losses are 10% in the housing units (Poulsen, 2008). However, in this manure cooling scenario, it is assumed that the CH₄ emissions are reduced by 50%. Accordingly, it is assumed that the DM losses are reduced by 50% as well.
c Same absolute reduction as DM.
d Change in Total-N: N from straw (same as reference system) minus emissions of NH₃-N, N₂O-N, NO-N and N₂-N (indirect emissions of N₂O-N not included). N added by straw: 0.00528 kg N/kg dm: Møller et al. (2000)
e P from added straw as in reference system. 0.0009 kg P/kg dm: Møller et al. (2000)
f K from added straw as in reference system. 0.015 kg K/kg dm: Møller et al. (2000)
g Change in Total-C: C from added straw (same amount as in reference system minus emissions of CO₂-C and CH₄-C. 0.4563 kg C/kg DM (Mean value from Biolex database) (www.biolexbase.dk)
h Cu from added straw as in reference system. 3 mg Cu/kg dm: Møller et al. 2000
i Zn from added straw as in reference system. 46 mg Zn/kg dm: Møller et al. 2000
j The manure composition "ex-housing" is calculated relative to the amount after storage, i.e. 1000 kg / 1005.88 as the manure is more diluted.

4.2 Outdoor storage

The emissions for the outdoor storage are calculated as for the reference system, using the same algorithms, except for CH₄ and N₂O. For the remaining emissions, the same algorithms has been used (as in the reference system), however, the results are slightly different from the reference
system, as the manure composition has changed slightly (e.g. higher content of N ex-housing, as the NH₃ emissions in the housing units are reduced).

4.2.1 **CH₄ and CO₂ emissions**

In the reference system, CH₄ emissions are based on the IPCC (2006) algorithms⁶. In this Manure Cooling scenario, the CH₄ emissions are based on the same emission factors as in the reference system. However, this report focuses on changes in the manure chain and the purpose of the IPCC guidelines is to deliver data for preparing national emission inventories for “status quo”. Accordingly, is has been necessary to implement some modifications.

In IPCC (2006), the CH₄ emissions during the in-house storage of the pig slurry and during the outdoor storage are based on the VS content ex-animal. When the emission factors for the outdoor storage are based on the ex-animal VS content, it means that changes to manure handling in the housing units will not affect the emissions during the outdoor storage, and that is, of course, not correct. If the IPCC approach was used directly in this Manure Cooling scenario, the realistic consequences of introducing cooling of manure would not be reflected, as the cooling of manure reduces the VS ex-housing; accordingly, the CH₄ emissions after this, should also change. Thus, an estimate of a CH₄ emission factor for the outdoor storage based on VS ex-housing rather than VS ex-animal have been established.

In order to clarify this, the emission factor for the outdoor storage has to be related to the VS content ex-housing (instead of ex-animal). In order to do this correct, IPCC was contacted. In accordance with personal communication with Mr Nalin Srivastava, Technical Support Unit of the IPCC TFI (Srivastava, August, 2013) and according to personal communication with Barbara Amon, Leibniz-Institut für Agrartechnik Potsdam-Bornim e.V., Potsdam, Germany (August, 2013) it was clarified, that the IPCC (2006) factors are developed for manure systems, where the manure is stored either in-house or outdoor, and these factors are not directly transferrable to systems like the Danish system, where the manure first is stored in-house for a period, and after this transferred to an outdoor storage. The factors for in-house and outdoor storage should not simply be added, as this would lead to a double-counting of the emissions. The reason is that if a significant part of the CH₄ emissions have been emitted in the warm housing units, the CH₄ emissions from the following outdoor storage will probably be relatively lower.

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For the reference scenario, the CH$_4$ emission factors for in-house storage and outdoor storage of pig slurry is based on (IPCC, 2006)\footnote{Table 10.17 on page 10.44 and Table 10.18 on page 10.49 in the updated version from January 2013 of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Use” – Chapter 10: Emissions from Livestock and Manure Management.} with a MCF (methane conversion factor) factor of 10%, which applies for countries with an average annual temperature $<10^\circ$C (the average annual temperature in Denmark is 7.7$^\circ$C) for a “Liquid/slurry system with natural crust cover” (the crust is here the floating layer). The IPCC definition of the “Liquid/slurry storage system” is “Manure is stored as excreted or with some minimal addition of water in either tanks or earthen ponds outside the animal housing, usually for periods less than one year.” This gives a CH$_4$ emission factor at 0.0396026 kg CH$_4$/kg VS ex-animal\footnote{CH$_4$ emission factor based on IPCC (2006): 0.396026 kg CH$_4$/kg VS ex-animal (CH$_4$ max potential for fattening pig manure) * 10% (MCF value) = 0.0396026 kg CH$_4$/kg VS ex-animal. The number of digits does not reflect the precision, but are only included as the numbers are used for further calculations.}, which is, in the reference scenario interpreted as “a combined factor for in-house and outdoor storage”. In the reference scenario, this CH$_4$ emission factor has been distributed as 25% in-house and 75% to the outdoor storage; both factors based on the VS ex-animal (see the descriptions of the reference system for further details).

In this Manure Cooling scenario, the CH$_4$ emission factor for the outdoor storage has been related to the “ex-housing” VS content of the slurry instead of the “ex-animal” as follows:

- The “combined” CH$_4$ emission factor for “combined in-house and outdoor storage” in the reference scenario is 0.0396026 kg CH$_4$/kg VS ex-animal.
- CH$_4$ emission factor for housing units (reference scenario): 0.0396026 CH$_4$/kg VS ex-animal * 25% = 0.00990 CH$_4$/kg VS ex-animal
- CH$_4$ emission factor for outdoor storage (reference scenario): 0.0396026 CH$_4$/kg VS ex-animal * 75% = 0.029702 CH$_4$/kg VS ex-animal.
- CH$_4$ emission factor for outdoor storage related to VS ex-housing instead of VS ex-animal = 0.032864 kg CH4/kg VS ex-housing\footnote{Transfer from per kg VS content ex-animal to per kg VS ex-housing: The values for VS ex-animal and ex-housing are taken from the reference system: 0.029702 CH4/kg VS ex-animal (ref system) * 60.363 kg VS/ton manure ex-animal (ref system) * 1000 kg manure ex-animal / (54.442 kg VS/ton manure ex-housing (ref system) * 1002.08 kg manure ex-housing, ref system) = 0.032864 kg CH4/kg VS ex-housing = the ex-housing emission factor for CH4.}

The interpretation of the distribution of the CH$_4$ emissions between in-house storage (25%) and outdoor storage (75%) is significant for the results of this manure cooling scenario; if the distribution were opposite (75% of the emission during in-house storage, 25% outdoor), a reduction of the in-house CH$_4$ emissions has a much larger impact on the overall results. Thus, a sensitivity analysis has been carried out for this, see section 5.1.

The CO$_2$ emission factor is calculated using the same algorithms as in the reference system, i.e. 1.83 kg CO$_2$/kg CH$_4$ for pig slurry, as explained in Hamelin (2013)\footnote{CH$_4$ emission factor based on IPCC (2006): 0.396026 kg CH$_4$/kg VS ex-animal (CH$_4$ max potential for fattening pig manure) * 10% (MCF value) = 0.0396026 kg CH4/kg VS ex-animal. The number of digits does not reflect the precision, but are only included as the numbers are used for further calculations.}. 

\(7\) Table 10.17 on page 10.44 and Table 10.18 on page 10.49 in the updated version from January 2013 of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Use” – Chapter 10: Emissions from Livestock and Manure Management.

\(8\) CH$_4$ emission factor based on IPCC (2006): 0.396026 kg CH$_4$/kg VS ex-animal (CH$_4$ max potential for fattening pig manure) * 10% (MCF value) = 0.0396026 kg CH4/kg VS ex-animal. The number of digits does not reflect the precision, but are only included as the numbers are used for further calculations.

\(9\) Transfer from per kg VS content ex-animal to per kg VS ex-housing: The values for VS ex-animal and ex-housing are taken from the reference system: 0.029702 CH4/kg VS ex-animal (ref system) * 60.363 kg VS/ton manure ex-animal (ref system) * 1000 kg manure ex-animal / (54.442 kg VS/ton manure ex-housing (ref system) * 1002.08 kg manure ex-housing, ref system) = 0.032864 kg CH4/kg VS ex-housing = the ex-housing emission factor for CH4.
As the assumption of distributing the CH$_4$ emissions with to 25% in-house and 75% to the outdoor storage might be significant for the overall results, a sensitivity analysis has been carried out.

4.2.2 $N_2O$ emissions

As for CH$_4$ emissions, N$_2$O emissions are based on the IPCC (2006) algorithms. The same problem occurs: In the reference scenario, the IPCC (2006) factors are a combined factor that includes emissions from the in-house storage and the outdoor storage together, and this factor is based on the N ex-animal. In the reference scenario, the N$_2$O emission factor has been distributed as 30% in-house and 70% to the outdoor storage; both based on the N ex-animal.

As for the CH$_4$ emissions, the above approach does not reflect realistic consequences of introducing cooling of manure, as the cooling of manure reduces the N ex-housing; accordingly, the N$_2$O emissions during outdoor storage, should be transferred to “per kg N ex-housing”. Thus, an estimate of a N$_2$O emission factor for the outdoor storage based on N ex-housing rather than N ex-animal have been established, parallel to the calculations in section 4.2.1:

- Combined N$_2$O emission factor based on IPCC (2006) (for housing units PLUS outdoor storage all together): 0.005 kg N$_2$O-N per kg N ex-animal.
- N$_2$O emission factor for housing units: 0.005 kg N$_2$O-N per kg N ex-animal * 30% = 0.0015 kg N$_2$O-N per kg N ex-animal.
- N$_2$O emission factor for outdoor storage: 0.005 kg N$_2$O-N per kg N ex-animal * 70% = 0.0035 kg N$_2$O-N per kg N ex-animal.
- N$_2$O emission factor for outdoor storage, related to ex-housing instead of ex-animal: 0.003983 kg N$_2$O-N per kg N ex-animal.

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10 Section “5 CO2: CH4 ratio and calculation of methane potential” in in Hamelin (2013), Appendix D: Supporting Information for: Environmental Consequences of Different carbon Alternatives for Increased Manure-Based Biogas), page s60-s61.

11 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Use” – Chapter 10: Emissions from Livestock and Manure Management. IPCC (2006): For liquid/slurry storage, with a natural crust: 0.005 kg N2O-N per kg N ex-animal (Chapter 10, table 10.21, page 10.62).

12 Transfer from per kg N content ex-animal to per kg N ex-housing: The values for N ex-animal and ex-housing is taken from the reference system, please see the description of this for further details. 0.0035 kg N2O-N per kg N ex-animal * 6.00 kg N/ton manure ex-animal (ref system) * 1000 kg manure ex-animal / (5.2619 kg N2O-N per kg N ex-housing (ref system) * 1002.08 kg manure ex-housing, ref system) = 0.003983 kg N2O-N per kg N ex-housing = the ex-housing emission factor for N2O. The number of digits does not reflect the precision, but are only included as the numbers are used for further calculations.
### 4.2.3 Life cycle inventory data for the process “Outdoor storage”

The life cycle inventory data for the process “outdoor storage” for the manure cooling scenario is shown in table 4.4. These are the data entered in SimaPro.

**Table 4.4. Life inventory data for the process “Outdoor storage” for the manure cooling scenario.**

<table>
<thead>
<tr>
<th></th>
<th>All emissions per 1 000 kg manure ex-housing</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manure &quot;ex-housing&quot;</td>
<td>1 000 kg</td>
<td>The input to this process is 1 000.0 kg manure “ex-housing”. The emissions are calculated relative to this.</td>
</tr>
<tr>
<td>Straw</td>
<td>2.5 kg</td>
<td>Straw layer added during outdoor storage in order to establish a “floating layer” on top of the slurry. The life cycle data of straw production are not included in this study, as being regarded as a waste product from cereal production.</td>
</tr>
<tr>
<td>Water</td>
<td>20.4 kg</td>
<td>The water from precipitation.</td>
</tr>
<tr>
<td><strong>Output</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manure &quot;ex storage&quot;</td>
<td>1 019.28 kg</td>
<td>Reduced caused by DM loss, increased due to addition of water and straw, see table 3.4.</td>
</tr>
<tr>
<td><strong>Energy consumption</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.9 kWh</td>
<td>Electricity consumption: 1.2 kWh for stirring when straw is added as a cover, 1.2 kWh for stirring before pumping for transfer to field and 0.5 kWh for pumping. As in reference system (Wesnæs et al. (2009)).</td>
</tr>
<tr>
<td><strong>Emission to air</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>0.9516 kg CO₂-C i.e. 3.4891 kg CO₂</td>
<td>Same algorithms as in reference system: 1.83 kg CO₂/kg CH₄ for pig slurry.</td>
</tr>
<tr>
<td>Methane (CH₄)</td>
<td>1.4299 kg CH₄-C i.e. 1.9066 kg CH₄</td>
<td>See text in the section 4.2.1.</td>
</tr>
<tr>
<td>Ammonia (NH₃-N)</td>
<td>0.10533 kg NH₃-N</td>
<td>Same algorithms as in reference system: 2.5% of TAN ex-housing table 9.7. (Poulsen et al., 2008); the N ex-housing being estimated according to Poulsen et al. (2008), i.e.: N ex-animal minus NH₃-N losses in-house (and not accounting for other losses).</td>
</tr>
<tr>
<td>Nitrous oxide (N₂O-N), direct emissions</td>
<td>0.02232 kg N₂O-N</td>
<td>See text in the section 4.2.2.</td>
</tr>
<tr>
<td>Nitrous oxide (N₂O-N), indirect emissions</td>
<td>0.0010552 kg N₂O-N</td>
<td>Indirect emission from volatilization, same algorithms as in reference system: 0.010 kg N₂O-N per kg NH₃-N + 0.010 kg N₂O-N per kg NOₓ-N volatilized. (IPCC, 2006).</td>
</tr>
<tr>
<td>Nitrogen monoxide (NO-N) (representing total NOₓ)</td>
<td>0.000196 kg NO-N</td>
<td>Algorithm as in reference system: 0.0001 kg NO per kg TAN (EMEP-EEA (2010), Table 3.9). 0.75 kg TAN per kg N ex-hosing (Poulsen, 2008, Table 9.7, p.17). Total-N ex-housing: see table 2 above.</td>
</tr>
<tr>
<td>Nitrogen (N₂-N)</td>
<td>0.01261 kg N₂-N</td>
<td>Algorithm as in reference: 0.0030 kg N₂ per kg TAN (EMEP-EEA (2010), Table 3.9) and 0.75 kg TAN per kg N ex-hosing (Poulsen, 2008, Table 9.7, p.17). Total-N ex-housing: see table 4.3 above.</td>
</tr>
<tr>
<td><strong>Discharge to water</strong></td>
<td>None</td>
<td>Assumed to be zero, as leakages from slurry tanks are prohibited in Denmark.</td>
</tr>
<tr>
<td><strong>Discharge to soil</strong></td>
<td>None</td>
<td>Assumed to be zero, as leakages from slurry tanks are prohibited in Denmark.</td>
</tr>
</tbody>
</table>

*The number of digits does not reflect the precision, only included as the numbers are used for further calculations.*
4.2.4  Mass balances for the process “Outdoor storage”

Mass balances for the process can be followed in table 4.5.

Table 4.5. Mass balances for the process “Outdoor storage”.

<table>
<thead>
<tr>
<th>Manure composition kg per ton manure ex-housing</th>
<th>Mass balance: Change during indoor storage kg</th>
<th>Mass balance: Amount after storage kg</th>
<th>Manure composition kg per ton manure ex-storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mass</td>
<td>+19.28</td>
<td>1019.28</td>
<td>1000</td>
</tr>
<tr>
<td>DM</td>
<td>- 1.48</td>
<td>70.61</td>
<td>69.27</td>
</tr>
<tr>
<td>VS</td>
<td>- 1.48</td>
<td>56.54</td>
<td>55.46</td>
</tr>
<tr>
<td>Total N</td>
<td>- 0.129</td>
<td>5.475</td>
<td>5.371</td>
</tr>
<tr>
<td>Phosphorus (P)</td>
<td>+ 0.00191</td>
<td>1.21</td>
<td>1.19</td>
</tr>
<tr>
<td>Potassium (K)</td>
<td>+ 0.03188</td>
<td>2.87</td>
<td>2.82</td>
</tr>
<tr>
<td>Carbon (C)</td>
<td>- 1.409</td>
<td>32.32</td>
<td>31.71</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>+ 0.0000064</td>
<td>0.0309</td>
<td>0.0303</td>
</tr>
<tr>
<td>Zinc (Zn)</td>
<td>+ 0.000098</td>
<td>0.0905</td>
<td>0.0888</td>
</tr>
</tbody>
</table>

Important: The number of digits does not reflect the precision, but are only included as the numbers are used for further calculations

a Change in total mass: +2.5 kg added straw (as in reference system) + 20.383 kg added water (as in reference system) – Change in DM.
b Change in DM: + DM added by straw (as in the reference system) – DM losses. DM in straw:  850 kg DM/ton straw (Møller et al., 2000). DM losses: Danish losses are 5% during outdoor storage (Poulsen, 2008).
c Same absolute reduction as DM.
d Change in Total-N: N from straw (same as reference system) minus emissions of NH3-N, N2O-N, NO-N and N2-N (indirect emissions of N2O-N not included). N added by straw: 0.00528 kg N/kg dm: Møller et al. (2000)
e P from added straw as in reference system. 0.0009 kg P/kg dm: Møller et al. (2000)
f K from added straw as in reference system. 0.015 kg K/kg dm: Møller et al. (2000)
g Change in Total-C: C from added straw (same amount as in reference system – emissions of CO2-C and CH4-C. 0.4563 kg C/kg DM (Mean value from Biolex database) (www.biolexbase.dk)
h Cu from added straw as in reference system. 3 mg Cu/kg dm: Møller et al. 2000
i Zn from added straw as in reference system. 46 mg Zn/kg dm: Møller et al. 2000
j The manure composition "ex-housing" is calculated relative to the amount after storage, i.e. 1000 kg / 1005.81 as the manure is more diluted.

4.3  Application to field

4.3.1  Danish Fertiliser Legislation

In Denmark, the amount of pig manure is spread according to the content of nitrogen. According to EU legislation, manure and degassed plant biomass may only be spread in a quantity equal to maximum 170 kg N per hectare per planning period. The EU Directives are implemented in Danish national legislation, which means that 170 kg N per hectare per planning period is also the limit in Denmark. However, Denmark’s national legislation exceeds the requirements of EU Directives; for manure from pigs and poultry, Danish farmers may only spread a maximum of 140 kg of nitrogen in the form of pig slurry or poultry manure per hectare of land, compared to 170 kg in other European countries. The 140 kg N per ha is an average for the all the farm area (i.e. the farmer is
allowed to spread more to some crops provided that he then spreads less to other crops). The 140 kg N per ha is calculated as the total amount of N in the manure ex-animal (The Danish Environmental Protection Agency (2012), Landbrugsinfo (2007), Landbrug og Fødevarer (2013), Ministeriet for Fødevarer, Landbrug og Fiskeri (2013a) and Ministeriet for Fødevarer, Landbrug og Fiskeri (2013b)).

The calculations of the N content in the manure are based on the Danish Norm system (Poulsen (2008), Poulsen (2011), Poulsen (2012) and Ministeriet for Fødevarer, Landbrug og Fiskeri (2013a)).

Manure from Manure Cooling systems is an exception; As Manure Cooling is not mentioned in the Danish Laws, farmers are allowed to bring out the same amounts of manure per ha regardless of having a manure cooling system in the housing units. According to the Danish Environmental Agency (2011), it is most likely that most farmers will spread the same amounts of manure per ha for manure cooling systems as for the reference system. As the manure from manure cooling has a higher content of N in the manure ex-storage, this will most probably lead to increase yields (Danish Environmental Agency, 2011).

4.3.2 Fertilizer substitution

As mentioned in section 4.3.1 above, the farmer will bring out the same amount of manure in this Manure Cooling scenario as in the reference scenario. As the farmer will act as if the manure was untreated, it is also the same amount of fertilizers that are substituted as for the reference system. Table 4.6 below shows the calculation of avoided mineral fertilisers for the reference system (and not with the values for the manure from manure cooling, as explained in section 4.3.1).

The fertilizer substitution is modelled in SimaPro as negative values, as the mineral fertilizers are subtracted from the system. Avoided Process (subtracted from the system):

- Nitrogen fertilizer: Adjusted Ecoinvent process: “Calcium ammonium nitrate, as N, at regional storehouse, nitric acid from plant with catalytic tech.” with adjusted nitric acid process as described in Hamelin et al. (2014), Supporting Information, section 2.5 and with applied emissions from spreading (NH₃, N₂O, NOₓ and N leaching).
- Phosphorous fertilizer: Ecoinvent process: “Diammonium phosphate, as P₂O₅, at regional storehouse” (see Hamelin et al. (2014), Supporting Information, section 2.5)
- Potassium fertilizer: Ecoinvent process “Potassium chloride, as K₂O, at regional storehouse/RER” (see Hamelin et al. (2014), Supporting Information, section 2.5)
- Included in this is avoided spreading of mineral fertilizers, based on the Ecoinvent process: Fertilising by broadcaster / CH U (Wesnæs et al. 2009).
Table 4.6. Amount of marginal mineral fertilizers avoided (application of untreated raw pig manure to field in the reference system)

<table>
<thead>
<tr>
<th>Nutrients content in the manure fraction(s) applied, ex-storage</th>
<th>Units</th>
<th>Calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen (N)</td>
<td>5.045</td>
<td>A1 (From table 4.9)</td>
</tr>
<tr>
<td>Phosphorous (P)</td>
<td>1.191</td>
<td>A2 (From table 4.9)</td>
</tr>
<tr>
<td>Potassium (K)</td>
<td>2.826</td>
<td>A3 (From table 4.9)</td>
</tr>
</tbody>
</table>

Amount of land needed

- kg N per ha according to rule: 140 [kg N / ha] E1
- Amount of manure per ha (calculated as 1000 kg manure ex-storage): 27.75 [ton manure fraction / ha] D = E1 / A1
- Area (area needed for spreading 1000 kg manure fraction ex-storage): 0.0360 [ha / ton manure fraction] B = A1 / E1

Nitrogen - N

- Recommended amount of N for crop rotation: 150.3 [kg N / ha] K1 (From table 4.10 above)
- Plant availability of applied N: 0.75 [%] C1 (75% according to Danish Law)
- Applied “plant available” N in manure: 105.0 [kg N / ha] L1 = A1 * C1 / B
- Avoided N mineral fertilizers: 105.0 [kg N / ha] A1
- Avoided N mineral fertilizers - per 1000 kg manure applied: 3.783 [kg N / ton manure applied] N1 = "Avoided N" * B

Phosphorous - P

- Recommended amount of P for crop rotation: 23.2 [kg P / ha] K2 (From table 4.10 above)
- Applied P in manure: 33.0 [kg P / ha] L2 = A2 * D
- Avoided P mineral fertilizers: 23.2 [kg P / ha] A2
- Avoided P mineral fertilizers - per 1000 kg manure applied: 0.835 [kg P / ton manure applied] N2 = "Avoided P" * B

Additional calculations for P in order to calculate P leaching:

- P uptake by plants: 15.095 [kg P / ha] O2 From table S67 in Supporting information for Hamelin et al. (2014)
- P from manure added in excess amounts compared to uptake by plants: 18.0 [kg P / ha] R2 = L2 - O2 If 0 < R2, P is applied in excess amounts compared to plant uptake
- P from manure added in excess amounts compared to uptake by plants - per 1000 kg manure applied: 0.647 [kg P / ton manure applied] S2 = R2 * B
- P leaching, assumed 5% of excess amounts - per 1000 kg manure applied: 0.03235 [kg P / ton manure applied] T2 = 0.05 * S2

Potassium - K

- Recommended amount of K for crop rotation: 60.8 [kg K / ha] K3 (From table 4.10 above)
- Applied K in manure: 78.4 [kg K / ha] L3 = A3 / B
- Avoided K mineral fertilizers: 60.8 [kg K / ha] A3
- Avoided K mineral fertilizers - per 1000 kg manure applied: 2.192 [kg K / ton manure applied] N3 = "Avoided K" * B

4.3.3 Increased Yield

As mentioned in section 4.3.1 above, the farmer brings out the same amount of manure regardless of having a manure cooling system in the housing units in accordance with Danish Law. Accordingly, the amount of manure per ha (in this Manure Cooling scenario) is identical to the amount of manure per ha in the reference system. As the manure contains a higher content of N (compared to the reference manure) an increased yield can be expected (Danish Environmental Agency, 2011).
A rough estimate of the increased yield is based on Wesnæs et al. (2009) (Annex B, section B.10) and Hamelin (2010) (Section F.28). Based on this, it is assumed that an extra amount of 1 kg N “available for the crop” (i.e. minus NH$_3$-N emissions) per 1000 kg slurry ex-storage corresponds to an increased yield of 12 kg crop$^{13}$. The yield changes reflect the difference in the “extra amount of N available” for “extra crop uptake” in the Manure Cooling Scenario as compared to the Reference System.

In this Manure Cooling scenario, the N available for the crop is 4.710 kg N per 1000 kg slurry ex storage (when using the same calculation as in Wesnæs et al. (2009)$^{14}$, whereas the N available for the crop for the reference system is 4.422 kg N per 1000 kg slurry ex storage$^{15}$. Accordingly, an additional amount of 0.288 kg N is available for the Manure Cooling scenario, which corresponds to an increased yield of 3.46 kg crop per 1000 kg slurry ex-storage$^{16}$. The amount of increased crop has been subtracted from the system, assumed to be winter wheat. The increased yield is modelled in SimaPro as the “reacting crop mix” described in details in Hamelin (2013)$^{17}$. The

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13 The ratio between “extra yield” and “extra amount of N available” is based on the reference system and the acidification scenario from Wesnæs et al. (2009) (section B.10).

- The average yield of the crop rotation, with pig slurry based fertilization (reference system, Wesnæs et al., 2009): 6140 kg/ha.
- Extra yield (Acidification scenario, Wesnæs et al., 2009): 6.6% = 6140 kg/ha * 0.066 = 405 kg/ha
- With an applied amount of 30 tons slurry per ha (as in Wesnæs et al., 2009), the increased yield of 405 kg/ha corresponds to 13.5 kg extra crop per 1000 kg slurry.
- The N available for the crops for the reference system of Wesnæs et al. (2009) (calculated as the N available after ammonia losses i.e. kg N per 1000 kg slurry ex storage minus NH$_3$-N loss during application and minus NH$_3$-N loss after application): 4.30 kg N per 1000 kg slurry ex storage.
- The N available for the crop, Acidification system of Wesnæs et al (2009): 5.43 kg N per 1000 kg slurry ex storage
- Extra N available for the crop in the acidification system compared to reference system (Wesnæs et al. (2009): 5.43 kg N – 4.30 kg N = 1.13 kg N per 1000 kg slurry ex-storage.
- Accordingly, it is assumed that an extra amount of 1 kg N “available for the crop” (i.e. minus NH$_3$-N emissions) per 1000 kg slurry ex-storage corresponds to an increased yield of 12 kg crop.
- 13.5 kg extra crop per 1000 kg slurry / 1.13 kg N per 1000 kg slurry ex-storage = 12 kg extra yield per kg extra N

14 i.e. calculated as the N available after ammonia losses only: 5.371. kg N per 1000 kg slurry ex storage (table 4.4) minus 0.0164 kg NH3-N loss during application and minus 0.6446 kg NH3-N loss after application), see table 4.5.

15 i.e. calculated as the N available after ammonia losses: 5.043. kg N per 1000 kg slurry ex storage (see reference system) minus 0.0154 kg NH3-N loss during application and minus 0.6052 kg NH3-N loss after application), see reference system.

16 4.710 kg N – 4.422 kg N = 0.288 kg N extra. Increased yield = 12 kg crop / kg N extra * 0.288 kg N per 1000 kg slurry ex-storage = 3.46 kg crop.

17 Hamelin (2013), Appendix D. Supporting Information for Paper V. Environmental Consequences of Different carbon Alternatives for Increased Manure-Based Biogas, section 3.1.13 Reacting crop production (maize scenario) at page s25.
“reacting crop mix” is given per hectare. The average crop yield for winter wheat is 6140 kg per hectare (Wesnaes et al. (2009))

4.3.4 Phosphorous and Nitrate leaching

Leaching of N has been calculated by with the N-LES4 model (Kristensen et al., 2008), a continuously updated empirical model to predict N leaching from arable land based on 1200 leaching studies performed in Denmark during the last 15 years.

Losses of P to soil and water is estimated by a rough estimate, assuming that the P leaching correspond to 5% of the P applied in excess, based on Hamelin et al. (2011).

Furthermore, sensitivity analyses for the P leaching have been performed, using a Finnish model for estimating phosphorus losses (Ekholm et al., 2005). A 10-year simulation was carried out using a P calculation model. This P model is used to determine the initial and final phosphorus load. This model relates the P surplus (or deficit) in a farm to the edge-of-field losses of algal-available P. Based on long-term fertilizer trials, the model first estimates the change in soil-test P of top soil with the aid of the soil-surface balance of P. Soil-test P is then used to approximate the concentration of dissolved reactive P in surface runoff and drainage flow, as adjusted for different P application types. Particulate P is estimated from specific erosion rates for each soil type and a bioavailability coefficient of 0.16 was used.

4.3.5 Fate of Carbon in manures applied to soil, CO₂ and CH₄ emissions

Soils have an equilibrium C content which is the result of a balance between inflows (e.g. plant matter from above- and below-ground residues, manure, etc.) and outflows (e.g. decomposition, erosion, leaching of soluble C, etc.) to the soil pool. If outflows are greater than inflows, soil C decreases, while soil C increases if inflows are greater than outflows. Output flows are to a great extent determined by climate-specific parameters like temperature and precipitations, where higher temperature and moisture favour the soil biota activity (i.e. decomposition). However, any change affecting the activity of soil biota (e.g. change in oxygen availability due to soil compaction, change in soil pH) will result in greater or smaller decomposition. In this sense, any form of agriculture will disturb the soil equilibrium until a new equilibrium is eventually reached after many years of constant agricultural practices. When manure is applied to soils, part of the C it contains ends up in the soil C pool, while the rest of the C essentially ends up emitted as CO₂ to the atmosphere. A given manure handling technology involving that more C ends up in the soil C

18 Wesnaes et al. (2009), Annex B, section B.10 page 215.
pool (in comparison to the reference situation) would thus imply an overall decrease of C ending up in the atmosphere. On the other hand, some manure handling technologies could involve that native soil C is lost (if, for example, they involve a drastic decrease of C applied to soils in comparison to the reference situation), in which case an overall increase of C to the atmosphere would be observed. In order to reflect such a balance, an attempt was made in order to model the soil C changes induced as a consequence of the different manure management technologies studied within Baltic Manure.

Table 4.7 presents the breakdown considered for the fate of C in the different types of manure (with and without treatments) fractions involved in the LCAs performed within Baltic Manure (those applied to soil). These values are based on the work of Hamelin et al. (2010; 2014), where the dynamic soil C model C-TOOL, developed to calculate the soil carbon dynamics in relation to the Danish commitments to UNFCCC, was used. This model is parameterized and validated against long-term field experiments conducted in Denmark, UK and Sweden. Further description of the C-TOOL model is given in Petersen et al. (2002) and Petersen (2010). As opposed to many different soil C models, C-TOOL does not only consider the topsoil, but the whole 0-100 cm profile. The values presented in Table 4.6 should be seen as rough estimates, these could of course be improved by a country-specific breakdown based on each country soil’s properties. However, these estimates allow reflecting the complete C balance. The use of results from C-TOOL in manure LCAs are described in Hamelin et al. (2014)\textsuperscript{19} and Wesnæs et al. (2009)\textsuperscript{20}.

Table 4.7. Breakdown of the applied C from the different manure types between the atmosphere and soil pool

<table>
<thead>
<tr>
<th>Description of the applied material</th>
<th>CO\textsubscript{2}-C, as a % of the C applied (from manure ex-storage)</th>
<th>C ending up in the soil C pool, as a % of the C applied (from manure ex-storage)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw slurry (pig and dairy)</td>
<td>95%</td>
<td>5%</td>
</tr>
<tr>
<td>Digestate (mono-digestion)</td>
<td>100%</td>
<td>0%</td>
</tr>
<tr>
<td>Digestate (co-digestion with solid fraction or solid manure)</td>
<td>90%</td>
<td>10%</td>
</tr>
<tr>
<td>Digestate (co-digestion with grass)</td>
<td>85%</td>
<td>15%</td>
</tr>
<tr>
<td>Solid manure (raw; pig, horse and broiler)</td>
<td>75%</td>
<td>25%</td>
</tr>
<tr>
<td>Solid fraction, from separation (of raw manure and/or digestate)</td>
<td>80%</td>
<td>20%</td>
</tr>
<tr>
<td>Liquid fraction (from source-segregation and from separation of both raw manure and digestate)</td>
<td>100%</td>
<td>0%</td>
</tr>
</tbody>
</table>

The CH\textsubscript{4} emissions on the field are assumed to be negligible, as the formation of CH\textsubscript{4} requires an anaerobic environment, which is, under normal conditions, not the case in the top soil.

\textsuperscript{19} In section “8 Digestates’ carbon fate” in Hamelin (2014), Appendix D: Supporting Information for: Environmental Consequences of Different carbon Alternatives for Increased Manure-Based Biogas, page s67.

\textsuperscript{20} In Appendix A, section A.5.2 Emissions of CH4 and CO2 and section A.5.5 Nitrogen leaching
**4.3.6  Life cycle inventory data for the process “Application to field”**

The life cycle inventory data for the process “Application to Field” for the manure cooling scenario is shown in table 4.8. These are the data entered in SimaPro.

**Table 4.8. Life inventory data for the process “Application to field” for the manure cooling scenario.**

<table>
<thead>
<tr>
<th></th>
<th>All emissions per 1 000 kg manure ex-storage</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manure &quot;ex-storage&quot;</td>
<td>1 000 kg</td>
<td>The input to this process is 1 000.0 kg manure “ex- storage”. The emissions are calculated relative to this.</td>
</tr>
<tr>
<td>Transport of manure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>to field</td>
<td>10 ton*km</td>
<td>As for the reference system. Based on the Ecoinvent process: Transport, tractor and trailer/CH U. Includes diesel for the spreading and production of tractor, trailer and shed.</td>
</tr>
<tr>
<td>Spreading of manure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>on field</td>
<td>1 000 kg</td>
<td>As for the reference system. Based on the Ecoinvent process: Slurry spreading, by vacuum tanker / CH U.</td>
</tr>
<tr>
<td><strong>Output</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N in manure</td>
<td>3.783 kg N</td>
<td>N fertilizer replaced, identical to reference system. Incl. spreading</td>
</tr>
<tr>
<td>P in manure</td>
<td>0.835 kg P</td>
<td>P fertilizer replaced, identical to reference system.</td>
</tr>
<tr>
<td>K in manure</td>
<td>2.192 kg K</td>
<td>K fertilizer replaced, identical to reference system.</td>
</tr>
<tr>
<td>Increased yield</td>
<td>3.46 kg crop</td>
<td>Increased yield.</td>
</tr>
<tr>
<td><strong>Energy consumption</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emission to air</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>30.12 kg CO₂-C (110.5 kg CO₂)</td>
<td>Based on Danish C-TOOL model, see section 4.3.5</td>
</tr>
<tr>
<td>Methane (CH₄)</td>
<td>0 kg CH₄-C</td>
<td>The CH₄ emissions on the field are assumed to be negligible.</td>
</tr>
<tr>
<td>Ammonia (NH₃-N), at very moment of application</td>
<td>0.0164 kg NH₃-N</td>
<td>Ammonia emissions at very moment of application. Same algorithms as for reference system: 0.5% of TAN ex-storage for trail hose application (Hansen, 2008). TAN = 3.17/5.19 = 0.6108 kg TAN per kg N ex-storage (Based on ratio for pig manure ex-storage, Poulsen, 2011).</td>
</tr>
<tr>
<td>Ammonia (NH₃-N)</td>
<td>0.6446 kg NH₃-N</td>
<td>Ammonia emissions in the period after application. Same algorithms as for reference system: 12% of N applied i.e. N ex-storage. (Hansen et al., 2008).</td>
</tr>
<tr>
<td>Nitrous oxide (N₂O-N), direct emissions</td>
<td>0.05372 kg N₂O-N</td>
<td>Same algorithms as for reference system: 0.01 kg N₂O-N per kg N IPCC (2006) emission factor, for any organic amendment.</td>
</tr>
<tr>
<td>Nitrous oxide (N₂O-N), indirect emissions</td>
<td>0.0064997 kg N₂O-N</td>
<td>Indirect emission from volatilization, same algorithms as in reference system: 0.010 kg N₂O-N per kg NH₃-N + 0.010 kg N₂O-N per kg NOₓ-N volatilized (IPCC, 2006).</td>
</tr>
<tr>
<td>Nitrous oxide (N₂O-N), indirect emissions</td>
<td>0.0182 kg N₂O-N</td>
<td>Indirect emission from leaching. Algorithms as in reference system. From N leaching: 0.0075 kg N₂O-N per kg N leaching (IPCC, 2006).</td>
</tr>
<tr>
<td>Nitrogen monoxide (NO-N) (representing total NOₓ)</td>
<td>0.00065 kg NO-N</td>
<td>Algorithm as in reference system: NOₓ-N = 0.1 * direct N₂O-N (Nemecek and Kägi, 2007)</td>
</tr>
<tr>
<td><strong>Discharge to water</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrate leaching</td>
<td>2.42 kg N</td>
<td>Nitrate leaching to the water bodies. Based on N-LES4 model Kristensen et al. (2008).</td>
</tr>
<tr>
<td>Phosphorus leaching</td>
<td>0.032 kg P (0.00721 kg P)</td>
<td>Rough estimate: 5% of surplus P. Sensitivity analyses: Finish model (Ekholm et al., 2005)</td>
</tr>
<tr>
<td><strong>Discharge to soil</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>100% of the Cu in the manure applied.</td>
<td></td>
</tr>
<tr>
<td>Zinc (Zn)</td>
<td>100% of the Zn in the manure applied.</td>
<td></td>
</tr>
</tbody>
</table>
5 Life Cycle Assessment Results and Interpretation

5.1 Life cycle Assessment Results including sensitivity analyses

The results of the LCA of the Manure Cooling Scenario are shown in figure 5.1 together with the sensitivity analysis. The Reference Scenario is also represented in figure 5.1.

The following sensitivity analysis has been carried out:

- Sensitivity analysis 1: A lower cooling effect at: 30 W/m², using 32.6 kWh electricity, assuming a heat utilization of 20% of the 97.9 kWh heat produced, leading to a 26.4% reduction of the NH₃, CH₄ and CO₂ emissions (compared to the reference scenario), see section 4.1.1, 4.1.2 and 4.1.4.

- Sensitivity analysis 2: 100% utilization of the heat from the heat pump (used in e.g. the housing units for weaning pigs). Avoided heat: 180 kWh per 1000 kg manure (see discussion and description in section 4.1.4). 51% reduction of the NH₃, CH₄ and CO₂ emissions (compared to the reference scenario), see section 4.1.1, 4.1.2 and 4.1.4.

- Sensitivity analysis 3: Reduced ventilation as a consequence of manure cooling. Avoided electricity: 4.5 kWh per 1000 kg manure (see discussion and description in section 4.1.5).

- Sensitivity analysis 4: Alternative marginal electricity production for year 2020-2035. It is assumed that this is 100% wind. This assumption is probably overstated, but used as “ideal electricity consumption”.

- Sensitivity analysis 5: Combination of 2, 3 and 4 above: 100% utilization of heat, reduced ventilation and alternative marginal electricity.

- Sensitivity analysis 6: 50-50% distribution of CH₄ and N₂O emissions between in-house and outdoor storage, as described in section 4.2.1 and 4.2.2.
Figure 5.1 Results and sensitivity analyses. Environmental impacts per 1000 kg of pig slurry ex-animal. (a) Global warming (CO$_2$-equivalent), (b) Acidification (m$^2$ “unprotected ecosystems equivalent”) (c) Aquatic eutrophication, Nitrogen (Nitrate leaching) (N-equivalent) and (d) Aquatic eutrophication, Phosphorous (Phosphorous leaching) (P-equivalent).
5.2 Discussion

5.2.1 Global Warming

In figure 5.1, Manure Cooling of fattening pig slurry has been compared to the reference scenario. It can be seen that Manure Cooling has a higher contribution to Global Warming than the reference scenario, caused by the electricity consumption by the heat pump. The Global Warming contribution from the electricity consumption is partly counterweighted by the avoided heat production, but not totally. This is partly due to that it not possible to utilize all the heat in the housing units for fattening pigs (see section 4.1.4). Nevertheless, when the heat from the heat pump is utilised 100% of the time (sensitivity analysis no. 2), Manure Cooling still has a higher contribution to Global Warming than the reference system.

Only in a future scenario with a marginal electricity production based on 100% wind, manure cooling has a lower contribution to Global Warming than the reference system (sensitivity analysis no. 4 and 5), assuming that the heat replaced is based on fossil fuels (natural gas). However, a marginal electricity production based on 100% wind is an “ultimate situation”, which is not realistic; it requires that the manure cooling pump is only activated in windy conditions, and that Danish electricity in windy conditions is 100% based on wind. Furthermore, this scenario would probably increase the manure temperature in periods during the summer, leading to increased NH₃ emissions.

As discussed in section 2.1 and 4.3.5, biogenic CO₂ is included in this series of Life Cycle Assessments in order to illustrate the significance of soil uptake of carbon. Manure cooling does not influence soil uptake of carbon, still, it is interesting to see the results with and without biogenic CO₂ (figure 5.2).

In the right part of figure 5.2 (without biogenic CO₂), the contributions to Global Warming from in-house and outdoor storage is caused by CH₄ and N₂O emissions and the contributions from field is due to N₂O emissions from the applied manure. As can be seen from figure 5.2, the overall conclusions described above do not change if excluding biogenic CO₂ from the results.
Figure 5.2 Results and sensitivity analyses. Environmental impacts per 1000 kg of pig slurry ex-animal. Global warming (CO$_2$-equivalent). Left: Biogenic CO$_2$ included (same figure as figure 5.1a). Right: Biogenic CO$_2$ not included.

5.2.2 Acidification

Manure Cooling gives a lower contribution to the environmental impact category “Acidification”, which is primarily caused by reduced NH$_3$ emissions. The reductions in NH$_3$ emissions caused by the Manure cooling is obvious in figure 5.1 (b), and applies for all sensitivity analyses.

5.2.3 Aquatic eutrophication, Nitrogen

In the reference scenario, the main contributions to the impact category “Aquatic eutrophication, Nitrogen” come from airborne NH$_3$ emissions (19%) and nitrate leaching from the manure applied to fields (80%).

Manure cooling leads to reduced NH$_3$ emissions during in-house storage. However, this is counterweighted by a higher content of N in the manure, and when the manure is spread on the fields, it leads to a slightly higher contribution to nitrate leaching.
The application of manure to fields replaces mineral fertilisers. These are shown as “avoided mineral fertilisers” in figure 5.1 as negative values, because the application of mineral nitrogen fertilisers would have caused nitrate leaching. Although the manure from manure cooling has a higher content of N, it does not lead to changed amounts of avoided mineral fertilisers due to the Danish law, see section 4.3.1, 4.3.2 and 4.3.3.

All in all, there is no significant difference between the contributions to “Aquatic eutrophication, Nitrogen” when comparing the Manure Cooling scenario to the reference system.

5.2.4 Aquatic eutrophication, Phosphorous

For the reference system, the contributions to the environmental impact category “Aquatic eutrophication, Phosphorous” mainly come from phosphorous losses from soil, originating from the manure applied to fields (93%).

Manure cooling does not affect the content of phosphorous in the pig slurry, and accordingly, there is not increase or decrease of phosphorous leaching from the manure applied to field, compared the reference system.

Contributions to “Aquatic eutrophication, Phosphorous” also come from energy production, mainly electricity production. For the reference system, the contribution from energy production is relatively small (7%). For the Manure Cooling scenario, however, the contribution from electricity production for the heat pump is significant, see figure 5.1. When analysing the results in SimaPro, the contributions from the electricity production mainly arise from the process “Disposal, spoil from coal mining, in surface landfill/GLO U”, i.e. from mining of coal. The uncertainty on the contribution from this process is probably high. As can be seen from figure 5.1 (sensitivity analysis no. 4), that a change in electricity consumption from coal to wind eliminates the difference, however, as discussed in section 5.2.1 above, 100% wind is hardly realistic. Nevertheless, electricity based on natural gas also reduces the contributions to “Aquatic eutrophication, Phosphorous” from the Manure Cooling scenario to a level comparable to the reference system. If the marginal electricity was not based on hard coal, but e.g. a mixture of natural gas and wind, there would be no significant difference between the contributions to “Aquatic eutrophication, Phosphorous” for Manure Cooling and the reference scenario.

As described under “Aquatic eutrophication, Nitrogen”, the application of manure to fields replaces mineral fertilisers. These are shown as “avoided mineral fertilisers” in figure 5.1 as negative values, because production of the mineral fertilisers leads to significant phosphorous losses and because application of mineral fertilisers would have caused phosphorous losses. Still, manure cooling does not influence the amount of avoided mineral phosphorous fertilisers compared to the reference system.
A sensitivity analysis has been performed, using a Finish model for phosphorous leaching, see section 4.3.4. The phosphorous leaching is significantly smaller when using this model; however, it does not change the overall conclusions.

5.3 Conclusion

The Manure Cooling Technology reduces ammonia emissions in the housing units, which leads to a higher N content in the manure. The technology is based on a heat pump, which requires electricity; however, it also produces heat that can replace other sources of heat for e.g. heating the housing units for the pigs. The heat produced by the heat pump is typically 3 times the amount of electricity. The environmental impacts has been assessed along the “manure management chain” from in-house storage, outdoor storage and to field application in combination with the environmental impacts from the energy production for the manure cooling. From this perspective, it can be concluded that:

- Manure Cooling gives a lower contribution to the environmental impact category “Acidification”, which is primarily caused by reduced NH$_3$ emissions.

- Manure Cooling has a higher contribution to Global Warming than the reference scenario, caused by the electricity consumption by the heat pump. The contribution from the electricity consumption is partly counterweighted by the avoided heat production, but not totally, not even when the heat from the heat pump is used 100% of the time. Only when using an “optimal electricity production” (from a CO$_2$ point of view), i.e. 100% wind, the Manure Cooling scenario can compete with the reference system, however, this is not regarded as realistic (today).

- Manure Cooling does not lead to any significant changes for the environmental impact category “Aquatic eutrophication, Nitrogen” (which is mainly caused by nitrate leaching and NH$_3$ emissions).

- Manure Cooling does not change the phosphorous content of the slurry and accordingly, the phosphorous losses from soil from the applied manure is not changed compared to the reference system. However, the electricity consumption for the heat pump leads to indirect phosphorous leaching from coal mining as the calculations were based on Danish electricity production from coal (which might be regarded as the “marginal” electricity today). If the Danish electricity consumption is based on a mixture of natural gas and wind, the phosphorous leaching from the electricity consumption is insignificant.
In this context, it should be mentioned, that it is important to prevent NH$_3$ emissions in the rest of the manure chain, i.e. during the outdoor storage and during field application of the slurry in order not to lose the environmental benefit of Manure Cooling. Accordingly, Manure Cooling should not be installed alone, but followed by effective reductions in the following steps (e.g. tight covering of the outdoor storage and field application of the slurry by use of trailing hoses/bandspreading or injection into the soil).

Conclusions on Manure Cooling of slurry in housing units for piglets, sows or dairy cows or in other countries cannot be drawn on the basis of this report; these systems are different from the fattening pig slurry analysed in this report (for example, all the heat might be utilised in housing units for piglets, or, the time the slurry is stored in-house might be significantly shorter than in the Danish system for fattening pigs). It is necessary to conduct a Life Cycle Assessment for these systems in order to identify if the conclusions are parallel.

In short; The environmental benefit of Manure Cooling is reduced NH$_3$ emissions in the housing units, however, this is at the expense of a higher contribution to Global Warming due to the electricity consumption, at least when is based on coal (the marginal electricity production in Denmark today).

Taking everything into account, it is worthwhile considering if it is preferable from an environmental point of view to keep the pig slurry in the housing units for 15-30 days or more (typical in Denmark today) and use energy for cooling, rather than shortening the in-house storage time for the pig slurry to 1 day (as in many of Denmark’s neighbour countries) and transferring the pig slurry to outdoor conditions immediately, which, in Denmark, has an average year temperature of 7.7 °C.
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The Baltic Sea Region is an area of intensive agricultural production. Animal manure is often considered to be a waste product and an environmental problem. The long-term strategic objective of the project Baltic Manure is to change the general perception of manure from a waste product to a resource. This is done through research and by identifying inherent business opportunities with the proper manure handling technologies and policy framework.

To achieve this objective, three interconnected manure forums has been established with the focus areas of Knowledge, Policy and Business.

Read more at www.balticmanure.eu.

This report in brief

The Manure Cooling Technology reduces ammonia emissions in the housing units, which leads to a higher N content in the manure (which might increase nitrate leaching). The technology is based on a heat pump, which requires electricity; however, it also produces heat that can replace other sources of heat for e.g. heating the housing units for the pigs. The environmental consequences of the technology are not straightforward: What are the environmental advantages and disadvantages of applying manure cooling in the housing units for fattening pigs?

The environmental impacts has been evaluated along the "manure management chain" from in-house storage, outdoor storage and to application of the manure to field in combination with the environmental impacts from the energy production for the manure cooling, by use of consequential Life Cycle Assessment (LCA).

This report on Manure Cooling was prepared as part of Work Package 5 on Assessing Sustainability of Manure Technology Chains in the project Baltic Manure.

About the project

The Baltic Sea Region is an area of intensive agricultural production. Animal manure is often considered to be a waste product and an environmental problem.

The long-term strategic objective of the project Baltic Manure is to change the general perception of manure from a waste product to a resource. This is done through research and by identifying inherent business opportunities with the proper manure handling technologies and policy framework.

To achieve this objective, three interconnected manure forums has been established with the focus areas of Knowledge, Policy and Business.

Read more at www.balticmanure.eu.