KNOWLEDGE REPORT

Life Cycle Inventory & Assessment Report: Cooling of Manure, Applied to Fattening Pig Slurry, Finland

By Juha Grönroos, Katri Rankinen, José E. Cano-Bernal, Lauri Larvus and Laura Alakukku

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

Life Cycle Inventory & Assessment Report: Cooling of Manure, Applied to Fattening Pig Slurry, Finland

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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 Finland.

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 Juha Grönroos and Katri Rankinen (Finnish Environment Institute SYKE), and Lauri Larvus and Laura Alakukku (University of Helsinki). Internal review for the inventory analysis of the LCA was performed by Andras Baky from the Swedish Institute of Agricultural and Environmental Engineering (JTI).

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The authors
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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 myriad 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 WP5 final report.

1.2 Scope and objectives of this 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 Finland.
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-y project started in 2011 and ended in 2013.

The participants of WP5 include:

- Lorie Hamelin, Henrik Wenzel, Marianne Wespæs & Henrik Saxe; University of Southern Denmark
- Juha Grönroos, Katri Rankinen & José E. Cano-Bernal; Finnish Environment Institute SYKE
- 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 Ziolkowski & 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; www.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. 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 fertilizers) 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).

Internal peer review for the inventory analysis part of the LCA was performed by Andras Baky from the Swedish Institute of Agricultural and Environmental Engineering (JTI).

2.2 Background and objective

Ammonia emissions and odours arising from manure cause effects on the environment and on human and animal health. Liquid manure (slurry) cooling in manure channels effectively decreases gaseous emissions from manure. Cooling by a heat pump requires extra electrical energy but the recovered heat can be used in heating the animal shelters and cleaning water, avoiding the use of the prevailing heat energy sources.

The objective of this LCA was to compare, in terms of life cycle environmental impacts, fattening pig slurry system with manure cooling and heat recovery, to a reference system, the fattening pig slurry system without manure cooling.
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 was 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 further specified in the description of the reference system, see Hamelin et al. 2013a.

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 was put on the differences, and the processes, that are identical for the reference scenarios and the alternative technologies were 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 boundary 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 fertilization operations (slurry application and slurry fate in the soil).

A reference crop rotation was 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. It is supposed that in manure management systems with increased slurry N concentration - compared to the reference system - does not have an effect on the slurry application acreage but affects the mineral fertilizer N need, thus reducing the use of mineral N.

In the LCA, biogenic CO₂ was included in the climate impact assessment. The reason for this was the aim to demonstrate how different manure management systems affect the fate of manure carbon (C) and the potential C sequestration capacity of them. If the biogenic C-loss – as CO₂ - in a manure management system is small, the potential C sequestration into soil after manure application is high, and vice versa. The more C is sequestered into soil for a long time period, the higher is the benefit from the climate point of view. This can be seen as a low climate impact value caused by the biogenic CO₂ emissions.
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 Finland. The reference scenario can be summarized as the following three main stages: in-house storage, outdoor storage and application to field.

Once excreted, the pig manure is then stored in-house in the slurry pit below the animals for approximately 2-3 weeks. On a regular basis, the pits are emptied to an outdoor storage tank, made of concrete. It is assumed that the storage tank is covered with mixed roofing according to the estimated roofing ratios in Finland, based on the national ammonia emission model for agriculture (Grönroos et al. 2009). The slurry will remain in the storage tank until the suitable period for field fertilization. When suitable, the slurry will be pumped from the storage tank, transported to the field and applied to the fields to be fertilized. See figure 2.1.

Figure 2.1: System Boundaries for the reference system

2.4.2 System boundaries for the Manure Cooling scenario

The technique covered by this report is cooling of manure from fattening pigs. The manure cooling takes place in the housing units.

Ammonia volatilization from manure is dependent on the temperature of the manure; accordingly, cooling of the manure reduces the ammonia evaporation. Manure cooling also reduces CH$_4$ and CO$_2$ emissions as the lower temperature reduces 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 on 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). Manure cooling is mainly interesting for pigs on a 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, as well as a higher leaching of nitrate at the field, 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”](image)

### 2.5 Temporal, geographical and technological coverage

The study was based on data from the most recent year for which consistent data are available. It is the intention, that data used for this study should apply for 2011 and 5-7 years ahead. The scenario in this report covers manure management under Finnish conditions (e.g. housing systems, storage facilities, soil types, application methods, energy production and legislation regarding fertilization and nutrient substitution). Furthermore, the slurry composition varies significantly within the European countries due to differences in on-farm management, e.g. for feeding. Accordingly, 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. Manure Cooling is considered as “Best available technology” (BAT) in the BAT reference document for intensive rearing of pigs and poultry (EC 2003).

### 2.6 Data

The Finnish-specific manure management data for the reference system and manure cooling system were based on the expert opinions of the experts in MTT Agrifood Research Finland and University of Helsinki. Manure composition data ex-animal were based on the calculations of MTT...
The project is partly financed by the European Union - European Regional Development Fund

Agrifood Research Finland (Nousiainen, 2013). Data for the manure cooling technique was mainly based on information from the Danish Environmental Protection Agency combined with Danish literature. Data on energy systems, energy and chemicals production and the technology used in the agricultural production systems were based on the Ecoinvent database (v2.2) (Frischknecht & Rebitzer, 2005).

The Finnish ammonia emission model for agriculture (Grönroos et al. 2009) was used to calculate ammonia emissions for the studied manure management systems. 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” (EMEP-EEA, 2009) from the European Environment Agency (and the 2010 update of this). When needed, these factors have been combined with data from various literature; see the references at the end of the report.

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. (2013b)).

3 Life Cycle Inventory data for Reference scenario

The Life Cycle Inventory data for the reference scenario is described in a report “Reference life cycle assessment scenarios for manure management in the Baltic Sea regions - An assessment covering six animal production, five countries, and four manure types” (Hamelin et al., 2013a). This section contains a summary only.

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, Finland are:

- A housing system with partly slatted floor.
- Once excreted, the pig manure is stored in-house in the slurry pit below the animals for approximately 2-3 weeks.
- On a regular basis, the pits are emptied to an outdoor storage tank, made of concrete. It is assumed that the storage tank is covered with mixed roofing according to the estimated roofing ratios in Finland.
- The transport distance from storage to application to fields has been estimated to 3 km.
- The slurry is applied on the fields using the estimated ratios of the different application measures of pig slurry in Finland.
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. (2013a).

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. (2013a).

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

<table>
<thead>
<tr>
<th>Manure stage</th>
<th>ex-animal</th>
<th>ex-housing</th>
<th>ex-outdoor storage</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mass (ton)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>Mass balance a</td>
</tr>
<tr>
<td>Dry matter (DM) (kg)</td>
<td>70.0</td>
<td>69.6</td>
<td>59.9</td>
<td>Nousiainen, 2013</td>
</tr>
<tr>
<td>Ash content (kg)</td>
<td>13.7</td>
<td>13.3</td>
<td>12.6</td>
<td>DM minus VS</td>
</tr>
<tr>
<td>Volatile solids (VS) (kg)</td>
<td>56.3</td>
<td>56.3</td>
<td>47.3</td>
<td>Same loss, in absolute, as DM</td>
</tr>
<tr>
<td>Carbon (C) (kg)</td>
<td>33.31</td>
<td>33.0</td>
<td>28.7</td>
<td>Mass balance d</td>
</tr>
<tr>
<td>Total N (kg)</td>
<td>5.36</td>
<td>4.73</td>
<td>3.991</td>
<td>Nousiainen, 2013</td>
</tr>
<tr>
<td>NH4+-N (kg)</td>
<td>3.48</td>
<td>3.07</td>
<td>2.59</td>
<td>Based on ratio in Viljavuuspalvelu, 2013</td>
</tr>
<tr>
<td>Phosphorus (P) (kg)</td>
<td>1.28</td>
<td>1.24</td>
<td>1.17</td>
<td>Nousiainen, 2013</td>
</tr>
<tr>
<td>Potassium (K) (kg)</td>
<td>2.14</td>
<td>2.11</td>
<td>1.995</td>
<td>Nousiainen, 2013</td>
</tr>
</tbody>
</table>

- a Change in total mass during in-house storage: +2.91 kg added straw + 28.6 kg added water minus change in DM.
- b Change in total mass during outdoor storage: +65 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: 3.16 kg VS loss per kg CH4 loss (3.16 gram VS loss per gram CH4 is based on the Buswell equation (Symons and Buswell (1933), using the same principles as in chapter 5 of the Supporting Information of Hamelin (2013)). However, in this Manure Cooling scenario, it is assumed that the CH4 emissions are reduced by 30%. The DM losses are reduced respectively.
- d Change in Total-C: C from added straw minus emissions of CO2-C and CH4-C.
- e 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)
- 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)
Table 3.2: Life Cycle Inventory data for the reference system, fattening pig slurry, Finland.

<table>
<thead>
<tr>
<th>Life cycle stage</th>
<th>Emissions</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In-house</td>
<td>Outdoor</td>
</tr>
<tr>
<td></td>
<td>per 1000 kg manure ex-animal</td>
<td>per 1000 kg manure ex-housing</td>
</tr>
<tr>
<td>NH₃-N</td>
<td>0.480</td>
<td>0.475</td>
</tr>
<tr>
<td>NH₃-N, at application</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>N₂O-N</td>
<td>0.0080</td>
<td>0.0182</td>
</tr>
<tr>
<td>NO-N (representing NOₓ)</td>
<td>1.62×10⁻⁸</td>
<td>1.43×10⁻⁸</td>
</tr>
<tr>
<td>NO₂-N</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>N₂-N</td>
<td>0.0104</td>
<td>0.0092</td>
</tr>
<tr>
<td>CO₂-C</td>
<td>0.295</td>
<td>1.030</td>
</tr>
<tr>
<td>CH₄-C</td>
<td>0.177</td>
<td>1.548</td>
</tr>
<tr>
<td>P leaching</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indirect N₂O-N (due to emissions of NH₃ and NOₓ)</td>
<td>0.00480</td>
<td>0.00476</td>
</tr>
<tr>
<td>Indirect N₂O-N (due to NO₃ leaching)</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
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, Finland. Accordingly, it is recommended to read the description of the reference system first.

4.1 Cooling of fattening pig manure in the housing units

This section on data for cooling of manure is to a great extent based on the Danish LCA-report on manure cooling by Wesnæs et al. (2013).

4.1.1 NH₃ 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/m² cooling effect applied (Pedersen, 1997). Pedersen (1997) recommends a maximum cooling of 20 W/m² 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/m².

Danish tests with cooling slurry in housing units for sows in gestation pens show ammonia reductions of 31% with an average cooling effect of 24 W/m² (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:

For housing units with frequent slurry removal e.g. with mechanical removal:

\[
\text{NH}_3 \text{ reduction (\%)} = -0.008x^2 + 1.5x
\]

For traditional slurry system with 40 cm deep slurry canals:

\[
\text{NH}_3 \text{ reduction (\%)} = -0.004x^2 + x
\]

\[x = \text{cooling effect (in W/m}^2\)\]

The upper limit for the cooling effect is not stated.

The results of recent tests have shown a reduction in 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 30% (compared to the reference scenario) was applied. A sensitivity analysis was performed, using the maximum cooling effect mentioned, i.e. 55 W/m². This corresponds to a NH₃ reduction of 51%.

4.1.2 CH₄ and CO₂ emissions

For the “Manure Cooling scenario” in this study, it is assumed that the CH₄ emissions are on the same level as the NH₃ reductions, i.e. 30% (compared to the reference scenario). The uncertainty
of the CH₄ reductions is considerable. Furthermore, it is assumed that the reduction of the CO₂ emissions is on the same level as the CH₄ reduction, i.e. 30% of the reference scenario (as the CO₂ and CH₄ emissions are interrelated, see the description CO₂-CH₄ ratio calculations in Hamelin (2013)¹).

In addition, the sensitivity analysis described in section 5.1 includes a reduction of the CH₄ and CO₂ emissions, assuming the same reduction level as for the NH₃ reductions, i.e. a reduction of 51%.

For more information on how manure cooling affects the emissions of CH₄, please see the Danish LCA-report on manure cooling (Wesnæs et al. 2013)

4.1.3 N₂O emissions

The N₂O emissions might change when cooling manure, however, Dustin (2002) cites two references, which observed that apparently, there were no relationship between temperature and N₂O emissions during storage. Accordingly, it is assumed that the N₂O 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 three 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 NH₃ emissions.

For the Manure Cooling Scenario in this study, an average emission reduction effect (30%) was applied. Based on the Table 4.1 this can be achieved with circa 35 kWh electricity consumption per one ton of slurry ex-animal, producing approximately three times of heat energy, i.e. 105 kWh per ton of slurry.

¹ 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.
Table 4.1: Cooling effect, electricity consumption and NH$_3$ reductions for manure cooling, fattening pigs.

<table>
<thead>
<tr>
<th>Cooling effect [kWh/m$^2$]</th>
<th>Electricity consumption [kWh per ton manure ex-animal]</th>
<th>Heat produced [kWh per ton manure ex-animal]</th>
<th>NH$_3$ reduction [%]</th>
<th>Reference and comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 W/m$^2$</td>
<td>10.9 kWh $^a$</td>
<td>32.6 kWh $^b$</td>
<td>9.6% $^c$</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/m$^2$</td>
<td>21.8 kWh $^d$</td>
<td>65.2 kWh $^b$</td>
<td>18.4% $^c$</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/m$^2$</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/m$^2$</td>
<td>32.6 kWh $^b$</td>
<td>97.9 kWh $^b$</td>
<td>26.4% $^c$</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/m$^2$</td>
<td>60 kWh $^f$</td>
<td>180 kWh $^b$</td>
<td>51%</td>
<td>Based on tests. Jørgensen et al. (2013). 51% NH$_3$ reduction based on tests.</td>
</tr>
<tr>
<td>Not stated</td>
<td>11.2 kWh</td>
<td>33.6 kWh $^b$</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).</td>
</tr>
</tbody>
</table>

a For a cooling effect of 10 kWh/m$^2$ 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 perDE 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: NH$_3$ reduction (%) = −0.004x$^2$ + x, where x = cooling effect (in W/m$^2$).
d For a cooling effect of 20 kWh/m$^2$ 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 perDE 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/m$^2$ 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 perDE 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/m$^2$. For fattening pigs on 25-49% solid floor the cooling area should be calculated as 0.47 m$^2$ per fattening pig (Danish Environmental Protection Agency, 2009). A Danish fattening pig produces in average on 0.47 m$^2$ 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 m$^2$ floor area / 2 W cooling effect per W electricity x 0.47 m$^2$ floor area per fattening pig / 0.47 m$^2$ manure per pig x 2184 hours = 60.06 kWh electricity per m$^3$ manure. As the energy consumption and heat produced are rounded numbers, and as the density of the reference pig slurry is 1053 kg per m$^3$, they are almost identical per m$^3$ 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.
In Finland, all heat produced cannot be utilized in the housing units for fattening pigs. According to Juha Takala from Pellon Group Oy approximately 2/3 of heat can be utilized (assuming that the excess heat cannot be used for the other purposes). This means that ca. 70 kWh of heat energy is utilized, but is, however, very rough estimate. For this reason, a sensitivity analysis assuming that all the heat from the heat pump can be utilized was carried out. This is calculated with the maximum cooling applied, corresponding to avoided heat of 105 kWh per 1000 kg manure, and the reductions in NH₃, CH₄ and CO₂ by 30%.

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. It is assumed that that light fuel oil is the marginal heat source avoided. The Ecoinvent process “Heat, light fuel oil, at boiler 100kW, non-modulating/CH U” was used in the modelling. The heat produced by oil is subtracted from the system, as this production is avoided if utilizing the heat produced by the heat pump instead. A sensitivity analysis was performed, assuming that heat production with woodchips is replaced with heat produced by heat pump. The Ecoinvent process “Heat, mixed chips from forest, at furnace 300kW/CH U” was used in the modelling for woodchips.

The electricity was modelled using the SimaPro process “Electricity, hard coal, at power plant/marginal Finland”.

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 humidity, dust, odour and emissions of e.g. hydrogen sulphide in the housing units. Accordingly, there is no direct relationship between the reduction in NH₃ emissions and the need for ventilation.

It was further assumed that ventilation is not altered in the housing unit equipped with manure cooling system.

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

In table 4.2 below, the life cycle 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, please, see detailed information on this in the separate reference report. The data in table 4.2 is the data entered in SimaPro.
Table 4.2: Life cycle inventory data for the process “Cooling of fattening pig manure in the housing units”. Note: The number of digits does not reflect the precision, but is only included as the numbers are used for further calculations.

<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 also the study’s functional unit. The emissions are calculated relative to this.</td>
</tr>
<tr>
<td>Straw</td>
<td>2.91 kg</td>
<td>As reference system.</td>
</tr>
<tr>
<td>Water</td>
<td>28.6 kg</td>
<td>As reference system.</td>
</tr>
<tr>
<td><strong>Output</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manure “ex-housing”</td>
<td>1 031.0 kg</td>
<td>Increased due to addition of water and straw, reduced caused by DM loss, see table 4.3.</td>
</tr>
<tr>
<td><strong>Energy consumption</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0 kWh</td>
<td>No energy for slurry pumping. In Finland, slurry is typically led to the outdoor storage directly, by gravity, after 2-3 weeks in-house storing.</td>
</tr>
<tr>
<td></td>
<td>+35 kWh</td>
<td>Electricity consumption for cooling.</td>
</tr>
<tr>
<td></td>
<td>-70 kWh</td>
<td>Assumption: 2/3 i.e. 70 kWh of heat produced by the heat pump and thereby potentially avoided. For sensitivity analysis 100% i.e.-105 kWh.</td>
</tr>
<tr>
<td><strong>Emission to air</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>0.206 kg CO₂-C</td>
<td>70% of reference system (30% reduction compared to reference).</td>
</tr>
<tr>
<td>Methane (CH₄)</td>
<td>0.124 kg CH₄-C</td>
<td>70% of reference system (30% reduction compared to reference).</td>
</tr>
<tr>
<td>Ammonia (NH₃-N)</td>
<td>0.320 kg NH₃-N</td>
<td>70% of reference system (30% reduction compared to reference).</td>
</tr>
<tr>
<td>Nitrous oxide (N₂O-N),</td>
<td>0.0056 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>0.0033 kg N₂O-N</td>
<td>Indirect emissions 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.</td>
</tr>
<tr>
<td>indirect emissions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrogen monoxide (NO-N)</td>
<td>0.00016 kg NO-N</td>
<td>Algorithm as in reference system: 0.0001 kg NO per kg TAN (EMEP-EAA (2009), Table 3.9). As TAN same as reference system, NO-N is the same, i.e. 0.000196 kg NO-N.</td>
</tr>
<tr>
<td>(representing total NOₓ)</td>
<td>Included in the above</td>
<td>Included in the above.</td>
</tr>
<tr>
<td>Nitrogen dioxide (NO₂-N)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrogen (N₂-N)</td>
<td>0.0104 kg N₂-N</td>
<td>Algorithms as in reference system: 0.0030 kg N₂ per kg TAN.</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 Finland.</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 Finland.</td>
</tr>
</tbody>
</table>
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</th>
<th>Mass balance: Change during indoor storage</th>
<th>Mass balance: Amount after storage</th>
<th>Manure composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mass</td>
<td>30.99 kg</td>
<td>1030.99 kg</td>
<td>1000 kg</td>
</tr>
<tr>
<td>DM</td>
<td>1.95 kg</td>
<td>71.952 kg</td>
<td>69.790 kg</td>
</tr>
<tr>
<td>VS</td>
<td>1.95 kg</td>
<td>58.255 kg</td>
<td>56.504 kg</td>
</tr>
<tr>
<td>Total N</td>
<td>-0.333 kg</td>
<td>5.027 kg</td>
<td>4.876 kg</td>
</tr>
<tr>
<td>Phosphorus (P)</td>
<td>0.002 kg</td>
<td>1.28 kg</td>
<td>1.244 kg</td>
</tr>
<tr>
<td>Potassium (K)</td>
<td>0.037 kg</td>
<td>2.18 kg</td>
<td>2.112 kg</td>
</tr>
<tr>
<td>Carbon (C)</td>
<td>0.799 kg</td>
<td>32.93 kg</td>
<td>31.936 kg</td>
</tr>
</tbody>
</table>

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

a Change in total mass: +2.91 kg added straw (as in reference system) + 28.6 kg added water (as in reference system) – Change in DM.

b Change in DM: + DM added by straw (as in reference system) – DM losses. DM in straw: 850 kg DM/ton straw (Møller et al., 2000). DM losses: 3.16 kg VS loss per kg CH₄ loss (3.16 gram VS loss per gram CH₄ is based on the Buswell equation (Symons and Buswell 1933), using the same principles as in chapter 5 of the Supporting Information of Hamelin (2013)). However, in this Manure Cooling scenario, it is assumed that the CH₄ emissions are reduced by 30%. The DM losses are reduced respectively.

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 The manure composition "ex-housing" is calculated relative to the amount after storage, i.e. 1000 kg / 1030.99 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 were 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) algorithms². However, IPCC (2006) use a combined factor that applies for the total emissions for the in-house storage PLUS the

² 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Use” – Chapter 10: Emissions from Livestock and Manure Management.
outdoor storage together, and this factor is based on the VS ex-animal. In the reference scenario, the CH$_4$ emission factor was distributed as 10% in-house and 90% to the outdoor storage, both based on the VS ex-animal (see reference system for further details).

In this scenario, the above approach will not reflect realistic consequences of introducing cooling of manure, as the cooling of manure reduces the VS ex-housing; accordingly, the CH$_4$ emissions after this should also change. Thus, an estimate of a CH$_4$ emission factor for the outdoor storage based on VS ex-housing rather than VS ex-animal were established.

Combined CH$_4$ emission factor based on IPCC (2006) (for housing units PLUS outdoor storage all together): 0.42 kg CH$_4$/kg VS ex-animal (CH$_4$ max potential for fattening pig manure) * 10% (MCF value) = 0.042 kg CH$_4$/kg VS ex-animal

CH$_4$ emission factor for housing units: 0.042 CH$_4$/kg VS ex-animal * 10% = 0.0042 CH$_4$/kg VS ex-animal

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)$^4$

4.2.2 N$_2$O emissions

As for CH$_4$ emissions, N$_2$O emissions are based on the IPCC (2006) algorithms. The same problem occurs: IPCC (2006) use a combined factor that applies for the total emissions for the in-house storage PLUS the outdoor storage together, and this factor is based on the N ex-animal. In the reference scenario, the N$_2$O emission factor was distributed as 30% in-house and 70% to the outdoor storage, both based on the N ex-animal (see reference system for further details).

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 changed when comparing to the reference scenario.

---

$^3$ The number of digits does not reflect the precision, but are only included as the numbers are used for further calculations.

$^4$ Section “5 CO$_2$: CH$_4$ 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.
scenario. Thus, an estimate of a N₂O emission factor for the outdoor storage based on N ex-housing rather than N ex-animal were established.

Combined N₂O emission factor based on IPCC (2006) (for housing units PLUS outdoor storage all together)⁵: 0.005 kg N₂O-N per kg N ex-animal.

N₂O emission factor for housing units: 0.005 kg N₂O-N per kg N ex-animal * 30% = 0.0015 kg N₂O-N per kg N ex-animal.

N₂O emission factor for outdoor storage: 0.005 kg N₂O-N per kg N ex-animal * 70% = 0.0035 kg N₂O-N per kg N ex-animal. However, we need this factor per kg N ex-housing, accordingly we use the N content ex-animal and ex-housing from the reference system to adjust this factor. 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 * 5.36 kg N/ton manure ex-animal (ref system) * 1000 kg manure ex-animal / (4.73 kg N/ton manure ex-housing (ref system) * 1030.8 kg manure ex-housing, ref system) = 0.00385 kg N₂O-N per kg N ex-housing = the ex-housing emission factor for N₂O.⁶

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.

---

⁵ 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).

⁶ The number of digits does not reflect the precision, but are only included as the numbers are used for further calculations.
Table 4.4: Life cycle inventory data for the process “Outdoor storage” for the Manure Cooling scenario. Note: The number of digits does not reflect the precision, but is only included as the numbers are used for further calculations.

<table>
<thead>
<tr>
<th>Input</th>
<th>All emissions per 1 000 kg manure</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<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>0 kg</td>
<td>No straw added during storing</td>
</tr>
<tr>
<td>Water</td>
<td>65 kg</td>
<td>The water from precipitation.</td>
</tr>
</tbody>
</table>

| Output | Manure "ex-storage" | 1 059.0 kg | Reduced due to DM loss, increased due to addition of water and straw, see table 3.4. |

| Energy consumption | 14.4 MJ | Fuel consumption: 14.4 MJ (0.35 litres) light fuel oil/ton manure and considering a LHV of 41.2 MJ/kg for light fuel oil. |

<table>
<thead>
<tr>
<th>Emission to air</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>1.091 kg CO₂-C</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>1.639 kg CH₄-C</td>
<td>See text in the section “CH₄ and CO₂ emissions” above this table.</td>
</tr>
<tr>
<td>Ammonia (NH₃-N)</td>
<td>0.485 kg NH₃-N</td>
<td>According to the Finnish ammonia emission model for agriculture (Grönroos et al. 2009); 9.4% of total N ex-housing.</td>
</tr>
<tr>
<td>Nitrous oxide (N₂O-N), direct emissions</td>
<td>0.0211 kg N₂O-N</td>
<td>See text in the section “N₂O emissions” above this table.</td>
</tr>
<tr>
<td>Nitrous oxide (N₂O-N), indirect emissions</td>
<td>0.0049 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.</td>
</tr>
<tr>
<td>Nitrogen monoxide (NO-N) (representing total NOₓ)</td>
<td>0.000148 kg NO-N</td>
<td>Algorithm as in reference system: 0.0001 kg NO per kg TAN (EMEP-EEA (2009), 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. Included in the above.</td>
</tr>
<tr>
<td>Nitrogen dioxide (NO₂-N)</td>
<td>Included in the above</td>
<td>Included in the above.</td>
</tr>
<tr>
<td>Nitrogen (N₂-N)</td>
<td>0.0095 kg N₂-N</td>
<td>Algorithm as in reference: 0.0030 kg N₂ per kg TAN and 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>
</tbody>
</table>

| Discharge to water | None | Assumed to be zero, as leakages from slurry tanks are prohibited in Finland. |

| Discharge to soil | None | Assumed to be zero, as leakages from slurry tanks are prohibited in Finland. |
### 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</th>
<th>Mass balance: Change during outdoor 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><strong>Total mass</strong></td>
<td>1000</td>
<td>58.67 a</td>
<td>1058.67</td>
</tr>
<tr>
<td><strong>DM</strong></td>
<td>69.79</td>
<td>-6.52 b</td>
<td>63.27</td>
</tr>
<tr>
<td><strong>VS</strong></td>
<td>56.50</td>
<td>-6.52 c</td>
<td>49.98</td>
</tr>
<tr>
<td><strong>Total N</strong></td>
<td>4.88</td>
<td>-0.503 d</td>
<td>4.373</td>
</tr>
<tr>
<td><strong>Phosphorus (P)</strong></td>
<td>1.24</td>
<td>0.002 e</td>
<td>1.25</td>
</tr>
<tr>
<td><strong>Potassium (K)</strong></td>
<td>2.11</td>
<td>0.036 f</td>
<td>2.15</td>
</tr>
<tr>
<td><strong>Carbon (C)</strong></td>
<td>31.94</td>
<td>-2.730 g</td>
<td>29.21</td>
</tr>
</tbody>
</table>

|                |                  |                                      | 1000                                        |

**Total mass:** 1000 kg.

**Change in total mass:** +65 kg added water (as in reference system) – Change in DM.

**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: 3.16 kg VS loss per kg CH₄ loss (3.16 gram VS loss per gram CH₄ is based on the Buswell equation (Symons and Buswell 1933), using the same principles as in chapter 5 of the Supporting Information of Hamelin (2013)).

**VS:** Same absolute reduction as DM.

**Total N:** 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).

**Phosphorus (P):** P from added straw as in reference system. 0.0009 kg P/kg dm: Møller et al. (2000).

**Potassium (K):** K from added straw as in reference system. 0.015 kg K/kg dm: Møller et al. (2000).

**Carbon (C):** 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).

**The manure composition “ex-housing” is calculated relative to the amount after storage, i.e. 1000 kg / 1068.67 as the manure is more diluted.**

### 4.3 Applying Manure to the field

The emissions from applying the manure to the field are based on the same algorithms as for the reference scenario, see the description of this for further details.

#### 4.3.1 CH₄ and CO₂ emissions

The CH₄ emissions on the field are assumed to be negligible, as the formation of CH₄ requires an anaerobic environment, which is, under normal conditions, not the case in the top soil.

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 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 4.6 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; 2013c), 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.

Table 4.6: 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>CO2-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>
4.3.2 Fertilizer substitution

The amounts of mineral fertilizer N, P and K substituted by the NH₄-N, P and K in the slurry are:

Nitrogen (N): 2.68 (kg/t pig manure ex-storage)
Phosphorus (P): 1.18 (kg/t pig manure ex-storage) x 73% = 0.86 (kg/t pig manure ex-storage)
Potassium (K): 2.03 (kg/t pig manure ex-storage)

The values are the same as the amounts of the nutrients in one ton of slurry ex-storage except for phosphorus for which a substitution rate of 73% was used. This was based on the differences in P fertilization limits in the Finnish agri-environmental support system between mineral and manure P. In an average situation mineral P application level for cereals is 11 kg/ha but in case of manure P fertilization level of 15 kg/ha can be applied. Based on this it can be argued that the difference (4 kg/ha) is P surplus and does not substitute mineral fertilizer P.

Reduced machine work due to reduced use of mineral fertilizers was not considered because it was assumed that a) manure nutrients do not fully satisfy the nutrient needs of the plants, meaning that mineral fertilizers must be applied on the whole acreage where manure was applied, and b) the all three main nutrients are applied at the same time using compound fertilizers.

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

- 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 (2013), section 2.5 and with applied emissions from spreading (NH₃, N₂O, NOₓ and N leaching).
- Phosphorus fertilizer: Ecoinvent process: “Diammonium phosphate, as P2O5, at regional storehouse” (see Hamelin (2013), section 2.5)
- Potassium fertilizer: Ecoinvent process “Potassium chloride, as K2O, at regional storehouse/RER” (see Hamelin (2013), section 2.5)

4.3.3 Increased Yield

In this Manure Cooling scenario, no increase in yields was expected. When the farmer brings out the pig manure to the fields, he will most probably spread the same amounts of manure regardless of having a manure cooling system in the housing units. As the manure contains a higher content of N (compared to the reference manure) an increased replacement of mineral N fertilizers can be expected.

4.3.4 Nitrate leaching

Nitrogen loads were calculated by an empirical model which was developed to predict annual average nitrate leaching as affected by the long-term rate of N fertilization and crop type by Simmelsgaard and Djurhuus (1998). The model was calibrated to each country by using country-
specific average N loss from fields and recommended N fertilization levels. In this manure management scenario an N loss of 15.19% of manure NH₄⁺-N was used.

4.3.5  **Phosphorus leaching**

The P loss from the fields was estimated by the model of Ekholm et al. (2005). The 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. In this manure management scenario a P loss of 1.5% of manure total phosphorus was used.

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 4.7. These are the data entered in SimaPro.
Table 4.7: Life inventory data for the process “Application to field” for the Manure Cooling scenario. Note: The number of digits does not reflect the precision, but is only included as the numbers are used for further calculations.

<table>
<thead>
<tr>
<th>Input</th>
<th>All emissions per 1 000 kg manure</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<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 to field</td>
<td>3 km*ton</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 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>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Output</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>NH₄-N in manure</td>
<td>2.68 kg N</td>
<td>N fertilizer replaced.</td>
</tr>
<tr>
<td>P in manure</td>
<td>1.18 kg P</td>
<td>P fertilizer replaced, see section 4.3.2.</td>
</tr>
<tr>
<td>K in manure</td>
<td>2.03 kg K</td>
<td>K fertilizer replaced.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Energy consumption</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel for transport and spreading of manure included in input above.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Emission to air</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>26.2 kg CO₂-C</td>
<td>Based on C-TOOL model, see section 4.3.1.</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>0.013 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).</td>
</tr>
<tr>
<td>Ammonia (NH₃-N)</td>
<td>0.660 kg NH₃-N</td>
<td>According to the Finnish ammonia emission model for agriculture (Grönroos et al., 2009); 16% of total N ex-outdoor storing.</td>
</tr>
<tr>
<td>Nitrous oxide (N₂O-N), direct emissions</td>
<td>0.0413 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 from volatilization</td>
<td>0.0066 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 from N leaching</td>
<td>0.0047 kg N₂O-N</td>
<td>Indirect emission from leaching. Same 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>0.0041 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>Nitrogen dioxide (NO₂-N)</td>
<td></td>
<td>Included in the above.</td>
</tr>
<tr>
<td>Nitrogen (N₂-N)</td>
<td>0.45 kg N₂-N</td>
<td>N₂ is only calculated in order to implement it in mass balances. According to Vinther and Hansen (2004), the N₂/N₂O ratio for “animal manure applied to field” is 3.5 for JB3 soils (Vinther and Hansen (2004), page 30, text above table 4), and accordingly, the N₂/N₂O-N factor is 11.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Discharge to water</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrate leaching</td>
<td>0.407 kg N</td>
<td>See section 4.3.4.</td>
</tr>
<tr>
<td>Phosphorus leaching</td>
<td>0.018 kg P</td>
<td>See section 4.3.5.</td>
</tr>
</tbody>
</table>
5 Life Cycle Assessment Results and Interpretation

5.1 Life cycle Assessment Results

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 analyses were carried out:

- **Sensitivity analysis 1**: 100% utilization of the heat from the heat pump. Avoided heat: 105 kWh per 1000 kg of manure (see discussion and description in section 4.1.4).

- **Sensitivity analysis 2a**: a higher emission reduction: cooling power 55 W/m², using 60 kWh electricity, assuming a heat utilization of 2/3 of the 180 kWh heat produced (replacing heat produced by light fuel oil), leading to a 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 2b**: Like S2a, but assuming a 100% utilization of heat (180 kWh) produced. Avoided use of light fuel oil as a source of heat, like in the basic case.

- **Sensitivity analysis 3**: Like the basic case, but avoided heat is produced by woodchips instead of light fuel oil.

- **Sensitivity analysis 4**: Like S2b, but heat produced by woodchips is avoided (instead of heat produced by light fuel oil).

- **Sensitivity analysis 5**: Like S2b, but the heat pump is operated by wind energy.
Figure 5.1: Global Warming (a; CO$_2$-eq), Acidification (b; m$^2$ unprotected ecosystems equivalent) and Aquatic Eutrophication N (c; N-eq) and P (d; P-eq) impact per 1000 kg of pig slurry ex-animal.
5.2 Discussion

Manure cooling of fattening pig slurry was compared to the reference scenario. From the figure 5.1 it can be seen that:

In the basic scenario, Manure Cooling has a higher contribution to Global Warming than the reference scenario, caused by the electricity consumption of the heat pump. In the basic scenario, the contribution from the electricity consumption is partly counterweighted by the avoided heat production. In the sensitivity analysis S1, where the heat is fully utilized, the Global Warming impact is equal with the reference scenario. The same applies for the sensitivity analyses with higher cooling effect (S2 and S3): if all heat is utilized and if the replaced heat is produced with oil, the Manure Cooling scenario has a same or slightly lower Global Warming impact compared to the reference scenario. In the sensitivity analyses S3 and S4 where the replaced heat is produced with woodchips, the Global Warming impact is the highest. When electricity used to operate the heat pump is based on renewable energy sources, e.g. wind, the Global Warming impact of the Manure Cooling scenario is the lowest (S5). From a Global Warming perspective, Manure Cooling is only an advantage in a future scenario, where the electricity used to operate the heat pump is based on renewable energy sources (i.e. with low CO₂ emissions).

Manure Cooling gives a lower contribution to the environmental impact category “Acidification”, which is primarily caused by NH₃ emissions, as it could be expected. The reductions in NH₃ emissions and in Acidification impact apply for all sensitivity analyses. However, the effect of manure cooling is somewhat small because of relatively short slurry in-house storing time in the Finnish piggeries.

Regarding the impact category “N aquatic eutrophication” (nitrate leaching, airborne nitrogen emissions), there are no major differences between the different manure management scenarios. Even though manure cooling decreases ammonia evaporation during animal housing, the decrease in emissions is so small (due to short slurry storing time in-house in Finland) that no clear effect can be seen. On the other hand, nitrate leaching has the main contribution to this impact meaning that changes in airborne N emissions do not have a significant effect on the impact value. There are differences in nitrate leaching because the Manure Cooling scenario results a somewhat higher N leaching compared to the reference. However, the differences are so small that they are counterweighted by the decrease in airborne N emissions.

Regarding the impact category “P aquatic eutrophication” (phosphorous leaching from the fields, phosphorus emissions to the waters from the industrial processes), manure cooling does not affect the content of phosphorous in the pig slurry. However, fertilizer industry and electricity generation do also contribute to this impact category. Accordingly, the electricity consumption of the heat pump leads to an increased contribution to this category. When analyzing the results in SimaPro, the contributions from the electricity consumption mainly arise from the process “Disposal, spoil from coal mining, in surface landfilling”. If the marginal electricity was not based on hard coal, as described in the main report, there would be no significant difference between the contributions to P aquatic eutrophication for Manure Cooling and the reference scenario.
5.3 Conclusions

Ammonia emissions from animal houses can be reduced using heat pumps to cool down manure. Heat energy obtained can be utilized for heating the animal houses or cleaning water, thus reducing the need for other heat sources. However, especially in Finland where time for storing slurry in-house is relatively short, the effect of ammonia emission reduction is small, even if effective cooling is used. The higher the cooling effect, the higher the use of electricity becomes. If all heat obtained cannot be utilized, the impact on climate change will rise due to electricity consumption. Important factor is how the electricity is produced. In consequential LCA marginal electricity is used, and in Finland it is electricity produced from coal. Only if climate neutral electricity is used and if heat is utilized even partly replacing fossil energy sources, the cooling system has a positive climate impact. From a Global Warming perspective, Manure Cooling is only an advantage in a future scenario, where the electricity used to operate the heat pump is based on renewable energy sources (i.e. with low CO₂ emissions).

To not lose the positive environmental impacts of manure cooling, obtained by reduced ammonia emissions during animal housing, it is important to prevent ammonia emissions effectively along the rest of the manure management chain. This is also important from the point of view of the negative environmental impacts of the manure cooling system: if the environmental benefits of the manure cooling are lost, also the environmental burdens (i.e Global Warming etc.) caused by the cooling are raised for nothing.

The impact of manure cooling on odours was not assessed. However, decreased ammonia emissions from housing decrease also odours. Additionally, it is possible that other compounds causing odours are reduced as well. Reducing ammonia emissions decrease also other harmful environmental impacts: direct damages to vegetation in high concentrations, secondary particle formation in atmosphere causing e.g. health effects to humans, and terrestrial eutrophication. Moreover, inside the animal houses, ammonia affects animal and human health.

If the heat pump is not possible to operate using carbon neutral electricity and if the heat produced cannot be utilized efficiently replacing fossil fuels, it is more recommendable from an environmental point of view to not use the heat pump but shorten the in-house storage time of slurry radically and by that way reduce ammonia and odors emissions.
6 References


countries, and four manure types. Baltic Manure WP5 Assessing Sustainability of Manure Technology Chains. Available at www.balticmanure.eu


Takala (2013), personal communication between Mr Juha Takala from the Pellon Group Oy, Finland and Juha Grönroos, Finnish Environment Institute (SYKE) combined with information from www.pellon.com/In_English/Home


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.

The Manure Cooling technology reduces ammonia emissions in the housing units leading to higher manure nitrogen content and decreasing the environmental impacts caused by ammonia. 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 animal house.

The study showed that if the heat pump is not possible to operate using carbon neutral electricity and if the heat produced cannot be utilized efficiently replacing fossil fuels, it is more recommendable from an environmental point of view to not use the heat pump but shorten the in-house storage time of slurry radically and by that way reduce ammonia and odors emissions.

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.