Life cycle environmental and economic impact assessment of pollution mitigation strategies implemented in European pig production systems

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Abstract

Pig production systems are significant contributors to environmental impacts arising from livestock and with the increasing demand for pork meat, their environmental footprint cannot be neglected. Many emerging technologies and alternative farm management practices have the potential to improve their environmental performance. However, the implementation of such practices is not always economically viable. Furthermore, their pollution mitigation potential can be sensitive to climate change and geographic variability. The aim of this thesis was to develop a whole-farm environmental abatement cost framework, able to evaluate the environmental and economic performance of pollution mitigation strategies from a life cycle perspective, while accounting for interactions between system components, climate change and spatial variability.

To fully understand and evaluate the environmental impacts associated with European pig production, a whole-farm, environmental Life Cycle Assessment (LCA) was developed on a typical Danish, integrated pig farming system. Through this model, potential environmental impact hotspots were identified related to pig housing and manure management. The abatement potential of a range of housing and manure management related pollution mitigation strategies was then evaluated. The results of this analysis showed that anaerobic digestion of slurry and in-house slurry acidification can significantly reduce the system environmental impact for a great range of impact categories.

Farm profitability was then evaluated through scenarios that simulated the implementation of the proposed pollution mitigation strategies, to determine their cost-effectiveness as stand-alone investments and through their combined implementation. For this purpose, an environmental abatement cost framework was developed by integrating the environmental LCA with a whole-farm economic model that considered capital costs, operating costs and all potential revenue streams. Anaerobic digestion of slurry was the most cost-effective strategy overall, achieving great environmental impact reductions while generating revenue and therefore increasing farm profitability.

The environmental abatement cost framework was then used to investigate the mitigation potential of two pig-cooling strategies that aim for ammonia emission reductions in a Swedish pig-fattening unit. Moreover, the framework was integrated with data on projected climate change for Sweden to evaluate the resilience and cost-effectiveness of these strategies against ambient temperature

increases. Both pig-cooling methods effectively mitigated heat stress related effects on animal performance, and significantly reduce system environmental impact, while improving farm profitability even under an intermediate climate change scenario.

Finally, the effects of geographic variability on the assessment of potential environmental and economic implications associated with the implementation of alternative manure management strategies in Danish pig farming systems were investigated. To achieve this, Geographical Information System (GIS) data and methods were integrated along with the environmental abatement cost framework. In doing so, spatially explicit environmental impact characterisation factors, regional policies that concern pig farming near nature-sensitive areas and agglomeration effects on the economy of the farm were taken into account. The analysis revealed significant effects of location on the cost-effectiveness of several environmental abatement strategies considered.

The methodologies developed and demonstrated in this thesis have the potential to guide decision making regarding farm investments that aim to improve system sustainability in a cost-effective manner.

Declaration

This thesis has been composed by me and has not been submitted as part of any previous application for a degree. All sources and information have been specifically acknowledged by means of referencing.

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Publications and conference presentations

From the research conducted in this thesis, the following publications have been produced and appear or submitted in peer-reviewed journals:

- Pexas, G., Mackenzie, S., Wallace, M., Kyriazakis, I. (2020a). Environmental impacts of housing conditions and manure management in European pig production systems through a life cycle perspective: A case study in Denmark. *Journal of Cleaner Production, 253*, 120005. doi: https://doi.org/10.1016/j.jclepro.2020.120005 **(Chapter 2)**
- Pexas, G., Mackenzie, S. G., Wallace, M., & Kyriazakis, I. (2020b). Cost-effectiveness of environmental impact abatement measures in a European pig production system. *Agricultural Systems, 182,* 102843. doi: https://doi.org/10.1016/j.agsy.2020.102843 **(Chapter 3)**
- Pexas, G., Mackenzie, S. G., Jeppsson, K. H., Olsson, A. C., Wallace, M., & Kyriazakis, I. (under review). Environmental and economic consequences of pig-cooling strategies implemented in a European pig-fattening unit. *Journal of Cleaner Production, 290,* 125784. doi: https://doi.org/10.1016/j.jclepro.2021.125784 **(Chapter 4)**
- Pexas, G., Mackenzie, S. G., Wallace, M., & Kyriazakis, I. (under review). Accounting for spatial variability in life cycle cost-effectiveness assessments of environmental impact abatement measures. *International Journal of Life Cycle Assessment (in press).* **(Chapter 5)**

The following work has been presented at conferences:

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- Pexas, G., Mackenzie, S., Wallace, M., Kyriazakis, I. Environmental impacts of housing and manure management in European pig production systems. *In:* Book of Abstracts of the 70th Annual Meeting of the European Federation of Animal Science, Session 18, Innovative approaches to pig production and pig research; Part 2: Wageningen Academic Publishers Early Career Competition, August 2019, Ghent, Belgium. **(Chapter 2)**

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- Pexas, G., Mackenzie, S., Wallace, M., Kyriazakis, I. Cost-effectiveness of environmental impact mitigation strategies in European pig production. *In:* Proceedings of the 12th International Conference on Life Cycle Assessment of Food, pp. 150-155, October 2020, Virtual from Berlin, Germany. **(Chapter 3)**

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List of Abbreviations

AAP	Aquatic Acidification Potential
Acid	Slurry Acidification
AD	Anaerobic Digestion
AEV	Annual Equivalent Value
AP	Acidification Potential
BAT	Best Available Techniques
BAU	Business As Usual
$CaCO_3$	Calcium Carbonate
CBA	Cost Benefit Analysis
CH_4	Methane
CO_2	Carbon Dioxide
DEFRA	Department of Environment, Food and Rural Affairs
DCF	Discounted Cash Flow
EAC	Environmental Abatement Cost
EI	Environmental Impact
EIC	Environmental Impact Category
EP	Eutrophication Potential
Eq	Equivalent
EU	European Union
FAO	Food and Agriculture Organisation
FCR	Feed Conversion Ratio
FEP	Freshwater Eutrophication Potential
FSR	Frequent Slurry Removal
g	Gram
GF	Growing / Finishing
GHG	Greenhouse Gas
GIS	Geographic Information System
GJ	Gigajoule
GWP	Global Warming Potential

H_2SO_4	Sulphuric Acid
HD	High Pig Farming Density
IMIN	Improved Insulation
IPCC	International Panel on Climate Change
IRR	Internal Rate of Return
ISD	Increased Slurry Dilution
ISO	International Organisation for Standardisation
IVE	Increased Ventilation Efficiency
JRC	Joint Research Centre
K	Potassium
kg	Kilogram
kWh	Kilowatt-hour
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LD	Low Pig Farming Density
LEAP	Livestock Environmental Assessment and Performance partnership
LU	Land Use
m^2	Square meter
m^3	Cubic meter
MACC	Marginal Abatement Cost Curve
MC	Monte Carlo
MEP	Marine Eutrophication Potential
MJ	Megajoule
N	Nitrogen
N_2	Atmospheric Nitrogen
N_2O	Dinitrogen Monoxide
NH_3	Ammonia
NH_4	Ammonium Ion
N-HD	Pig Farm Location Near Natura 2000 and High Pig Farming Density

N-LD	Pig Farm Location Near Natura 2000 and Low Pig Farming Density
NO_3	Nitrate
NO_x	Nitrogen Oxide
NPV	Net Present Value
NREU	Non-Renewable Energy Use
NRRU	Non-Renewable Resource Use
P	Phosphorus
PO_4^{3-}	Phosphate
RCP	Representative Concentration Pathway scenario
Sb	Antimony
SEGES	Danish Pig Research Centre
SI	Supporting Information
SLU	Swedish University of Agricultural Sciences
SO_2^-	Sulphate
SP	Screw Press Slurry Separation
TAP	Terrestrial Acidification Potential
USA	United States of America
ΔAEV	Difference in Annual Equivalent Value
ΔEI	Difference in Annual Environmental Impact

Chapter 1. General Introduction

The human population is projected to increase to more than 9 billion people by 2050, and with a consequent increase of food consumption rates it is believed we will need to produce approximately 70% more food globally, according to the Food and Agriculture Organization of the United Nations (FAO, 2009). Meat consumption specifically, has exhibited a rise of 63% over the last 40 years in Europe (FAO, 2018a), with pork meat being the most consumed meat product worldwide (FAOSTAT, 2019). To address the growing demand for pork meat, pig production systems have grown to form the largest sector by output in the meat industry globally (FAO, 2015a). The operation of such a major industry, in terms of production, is associated with the use of great amounts of resources. Ample amounts of feed and water are required for optimal animal growth. The construction, operation and maintenance of large facilities with controlled climate conditions are fundamental in facilitating efficient production and ensuring high animal welfare standards. Large amounts of fuel and energy are consumed for the operation of machinery involved in the various production stages, such as feed mills for diet formulations, ventilation and heating systems for indoor climate control, waste management systems etc.) (Stephen, 2012; FAO, 2018b). It has been estimated that pig production generates approximately 668 million tonnes of kg CO_2 equivalents annually on a global scale, due to such extensive use of inputs. (Macleod et al., 2013). Although significantly smaller than the 4623 million tonnes of CO2 equivalents per year produced by the beef and dairy supply chains, the increasing demand for pork meat suggests that the environmental impact of the sector cannot be neglected (McAuliffe, Chapman & Sage, 2016). Therefore, a key sustainability challenge of the 21st century is to reduce the environmental footprint of pig production systems, without sacrificing their productivity (European Commission, 2020). In this view, the global food system has to rely on the development of innovative sustainability methods to facilitate investments in novel strategies for more resource efficient, better environmental and economic performing pig supply chains (Macleod, 2013). For this reason, although the methods developed in this thesis can be applied to offer sustainable solutions for a variety of agricultural sectors, the core focus is pig production and the more specific case studies represent European pig farming systems.

Many studies have focused on evaluating the environmental impact of pig production systems as a whole for several environmental impact categories (Nguyen, Hermansen, & Mogensen, 2011; McAuliffe et al., 2016). Some have evaluated the contribution of the individual system components, including breeding stock traits (Ottosen, Mackenzie, Wallace & Kyriazakis, 2020), feed production (Basset-Mens & Van Der Werf, 2005; Mackenzie, Leinonen, Ferguson & Kyriazakis, 2016; Monteiro, Garcia-Launay, Brossard, Wilfart & Dourmad, 2016), pig housing (Philippe, Cabaraux & Nicks, 2011; Philippe & Nicks, 2015) and manure management (ten Hoeve et al., 2014), while investigating potential environmental impact mitigation measures associated with these components. According to these studies, the feed production component is the largest contributor to the environmental impacts arising from pig production systems, accounting for up to 65% of their global warming potential (GWP). Consequently, past research mainly focused on ways to improve system environmental performance by designing alternative, more sustainable diet formulations with novel ingredients, while adhering to breed-specific nutrient requirements for pig growth, and reduced concentrations of nutrients (e.g. phosphorus) that lead to hazardous emissions through animal excretions (e.g. eutrophication of freshwater ecosystems) (Garcia-Launay, Van der Werf, Nguyen, Le Tutour & Dourmad, 2014; Mackenzie et al., 2016; Nardina, Rigo, Paulo & Pozza, 2017). Fewer studies have shown that the potential impact of these animal related emissions is also directly or indirectly affected by a great variety of factors that describe management practices and efficiency of technologies involved at the pig housing and manure management components. According to literature, the most important of these effects have been associated with changes in temperature, humidity, air flow regimes and ventilation rates, slurry storage and slurry removal practices at pig housing, as well as slurry treatment, outside storage and application methods. Manure is a significant source of greenhouse gas, nitrogen-related and phosphorus-related harmful emissions associated with detrimental environmental impacts. Thence, any effect on manure composition that could aggravate these impacts should be carefully considered (Rigolot et al., 2010; Philippe et al., 2011; ten Hoeve et al., 2014; Philippe & Nicks, 2015 ; Dennehy et al., 2017). It is important when evaluating system environmental impacts to adopt whole-farm approaches that account for potential interactions between the different system components, which has not been the common practice to date.

Aside from mitigating system environmental impact, solutions that aim to improve pig farming sustainability must also address the economic and social pillars. Pig production systems must be developed in ways that ensure, at the same time, environmentally friendly and optimal productivity, without sacrificing the marketability of the product (Kebreab, 2013). While several environmental impact abatement measures have been proposed in the past, the environmental and economic consequences of their implementation have not always been fully explored.

1.1. Research Context: European pig production

The European Union is the largest pig meat exporter and second largest producer (after China) accounting for 22.8% of global production. Due to the increasing popularity of pork meat, and the strong focus on agri-environmental, animal welfare and food security related issues in Europe, facilitating the improvement of sustainability in European pig production has been an important topic for research and is the core focus of this thesis.

Within the European Union (EU), Denmark exhibits the highest share of pig production in agricultural output (29% of total) and leads by far the exporting of piglets in the EU (56.9% of total) (Marquer, Rabade & Forti, 2014; Eurostat, 2020). The country specialises both in breeding and fattening of pigs and it is defined mainly by integrated pig farming systems as will be described in detail in the following section. In addition to the important role that Denmark has in European pig production, it is characterised by homogeneity of pig production systems across the country, and good quality and easily accessible relevant data (Danish Pig Research Centre, SEGES). For these reasons, Danish pig production was used as a case study in Chapters 2, 3 and 5, for the development and application of the whole-farm environmental LCA and integrated, environmental abatement cost framework (Chapters 2, 3 and 5).

Alternatively, Chapter 4 presents a study that used Swedish pig production as a case in point. Past studies have revealed the importance to consider the effects of ambient temperature increase on livestock systems, even in places where heat stress has not been a major concern thus far. Sweden is such a place and its temperate climate is similar to that of the largest part of Central Europe, where a big portion of European pig production takes place (Vitt et al., 2017; Mikovits et al., 2019). Although it has a significantly smaller pig production sector than Denmark, it is among the ten European countries that share more than 30% of the large fattening pig farming units across the EU (Santonja et al., 2017). It therefore makes an interesting case study for the investigation of the effectiveness of pig cooling strategies using an LCA framework integrated with projected climate data. Furthermore, Swedish fattening-pig production shares many common characteristics with the Danish case study and also allows for detailed modelling due to ease of access for relevant data (Swedish University of Agricultural Sciences, SLU).

The following subsections provide an overview of the main characteristics that define representative cases of European intensive pig production, such as contemporary, conventional pig farming systems in Denmark and Sweden.

1.1.1. Contemporary pig farming systems and implications for the environment and economy

Although considerable variations have been identified in pig farming types, family-run integrated pig farming businesses seem to dominate intensive pig farming throughout Europe (Santonja et al., 2017).

Production and herd characteristics

Four distinct production stages are typically identified in a Danish, integrated pig farming system: i) 'gestation' including pregnant sows, ii) 'lactation' including nursing sows and piglets, iii) 'nursery' including weaning pigs up to 30 kg weight and iv) 'growing / finishing' (also addressed as 'fattening' stage) where pigs are reared till slaughter weight. A specialised pig-fattening unit imports weaners (~30 kg) from other breeding or integrated farms and focuses solely on the final production stage above (Nguyen et al., 2011; Santonja et al., 2017).

Substantial variability has also been identified in the choice of breeds reared across Europe (Marquer et al., 2014; Santonja et al., 2017). Farm managers select pig breeds on the basis of the potential economic benefits associated with animal traits specific to each breed, such as larger litters and faster animal growth. Offspring of Danish Landrace x Yorkshire sows and Duroc sires is the most common breed reared in the Danish pig farming systems. This breed is characterised by high litter sizes (~14 piglets per litter) and relatively low mortality rates throughout production (e.g. 13% piglet mortality after birth) (SEGES, personal communication). A 500-sow pig farm in Denmark produces around 13 thousand slaughter pigs per year at an average slaughter weight of 112 kg (Santonja et al., 2017; SEGES, personal communication). In Sweden, the animals most commonly reared in pig-fattening systems are offspring of Topigs Norsvin 70 sows x Hampshire sires. In contrast to the Danish case, this breed is not focused on high numbers of piglets, but traits related to vitality and growth such as the birth of heavier pigs and better feed conversion ratios for growth. These pigs grow from 30 kg to slaughter weight at 115 kg in an average period of 90 days, and therefore averaging three production cycles per year, the average size of production in a Swedish pig-fattening system is around 4 thousand slaughter pigs.

Many of the genetic and physical traits that characterise different pig breeds, such as different metabolic and growth rates, have important implications in the environmental performance and economy of a pig production system. As a consequence over the past decades intensive selective pressure has dominated the breeding component targeting specific objectives that improve system performance on these two aspects (de Vries, 1989; Skorupski, Garrick, Blair & Smith, 1995; Ottosen et al., 2020). While this thesis acknowledges the importance of accounting for variability in animal related traits when evaluating system environmental impact and financial performance, investigating such scenarios is outside of its scope.

Feed production

Feeding pigs is a complicated matter, as it requires complex combinations of feed ingredients not only supplying the animals with the required amounts of energy, essential amino acids, vitamins and minerals to achieve optimal growth at any developmental stage (Sprent, 2014), but doing so in the most cost-effective manner. Diet formulations are largely determined by the location of a pig farm and availability of feed ingredients in the local markets, and therefore large variability can be seen in feed production (i.e. home-mixing, pelleted form) and provision strategies (i.e. phase feeding) across Europe. Despite the diverse management plans regarding feeding, it is common for European pig farmers to own cropland where some of the more essential feed ingredients are grown, while purchasing the rest from local markets (Santonja et al., 2017). In the Danish and Swedish case studies that this thesis focuses, feed formulations for pig production are cereal-based and of very similar compositions with a few differences that mainly reflect the effect of location in crop production. For example, triticale is a common and increasingly popular ingredient found in Swedish diet formulations, instead of barley that is largely used in Denmark (Federation of Swedish Farmers – LRF, 2015; Danish Agriculture and Food Council, 2020)

The complexity of the feed production component and related management practices come with many environmental and economic consequences. The production of feed is considered as the largest contributor to environmental impacts arising from pig production systems. It accounts for a large percentage of system water footprint, land use, global warming, acidification and eutrophication potential impacts, due to the large amounts of water, fertilisers and pesticides required for this component (Basset-Mens & Van Der Werf, 2005; de Vries & de Boer, 2010;

Monteiro et al., 2016). Besides the many environmental implications, feed provision is the largest category of on-farm expenses, accounting for 60-70% of total production costs (Pomar & Remus, 2019). Furthermore, the uncertainty and volatility of pig feed prices is a high risk factor that can significantly affect not only the financial performance of the pig farming system but also have broader implications at the market level (Rezitis & Stavropoulos, 2009).

Many studies have evaluated and proposed several strategies to help improve system performance by reducing the potential impacts associated with this component. Precision feeding strategies and diets designed at an individual animal level (Pomar & Remus, 2019), alternative diet formulations using novel feed ingredients (Mackenzie et al., 2016) and innovative methods to facilitate diet formulation design that targets multiple objectives such as the reduction of global warming potential and cost of feed.

Pig housing

The majority of European intensive pig farming occurs in indoor, mechanically ventilated pig barns with the exception of only a few cases where a large percentage of sows are reared outdoors (e.g. 40% of sows in UK) (Santonja et al., 2017). This percentage in Denmark is as high as 98.9%, while only 1.1% of pigs are produced under organic standards (Pedersen, Schlaegelberger & Larsen, 2018).

In these intensive pig farming systems, different housing facilities and conditions are generally identified to better accommodate the animals' needs at each production stages. While this distinction is common across Europe, the specifications of the individual buildings can largely differ in terms of space, technologies involved for climate control, slurry handling, feed and water provision, management and many other factors, even within the same country or region (Santonja et al., 2017). Denmark is characterised by a relative homogeneity in pig housing facilities and management practices.

Despite potential large variations in design, we can identify the following main components in any pig housing facility across Europe and consider modifications of these components in terms of their implications for the sustainability of the pig farming system (Rigolot et al., 2010; Santonja et al., 2017).

i) ***The building, including the specific construction and insulation material, floor type, and other features.***

Construction materials generally do not exhibit big differences across different types of pig production systems, with concrete constructions (including walls, floor slats and roof slats) dominating throughout (Lammers, Honeyman, Harmon & Helmers., 2010a; Santonja et al., 2017). Some variation can be seen in the choice of insulation material, which is largely dictated by external climatic factors such as temperature and humidity. The most popular insulation material found in pig barns, mainly due to its low cost of purchase and installation, is fiberglass. The heat transfer coefficient 'U' measured in $W / m^2 \,°C^{-1}$ is generally used to express the effectiveness of insulation. None or poor insulation can result to unstable indoor climate conditions particularly when outdoor climate is variable. As a consequence, large increases in energy consumed for the operation of heating systems to compensate for heat losses may be required, leading to increased system environmental impact and poor economic performance. (Lammers et al., 2010b). The most common floor types found in European intensive pig production systems are fully slatted or partly slatted (e.g. 70:30 solid to slatted ratio). Partly slatted floors facilitate the separation of a distinct lying area (solid part) and dunging area (slatted part), thence significantly improving pen cleanliness and overall pen hygiene (Rantzer & Svendsen, 2001). Furthermore, it can help significantly reduce ammonia (NH_3) emissions if correctly cleaned (Aarnink & Elzing, 1998; Rigolot et al., 2010; Santonja et al., 2017). A European Directive on the protection of pigs sets the guidelines for the design of slatted floors for the different production stages, since it is important that the width of slats corresponds to animal growth (European Commission, 2008). Among other pig building characteristics to consider in the design of a pig barn when aiming for high sustainability standards, it is important to provide ample natural light through windows (double glazed optimally to avoid potential heat losses), or whenever this is not possible with the use of artificial light to ensure animals maintain a healthy diurnal cycle. An unstable diurnal cycle can lead to reduced metabolic rates, potential growth and therefore inefficient use of inputs for production (St-Pierre, Cobanov & Schnitkey, 2003; Patience, Umboh, Chaplin & Nyachoti, 2005; Lammers et al., 2010b).

ii) The climate control system, including the ventilation, heating, cooling systems and control unit.

Perhaps the most important roles of the pig housing component in animal production, are the provision of stable climate conditions according to the animals' thermal comfort zones for each developmental stage, the removal of harmful gases such as carbon dioxide, ammonia and methane, and the provision of ample fresh air at all times (Santonja et al., 2017; Mikovits et al., 2019; Schauberger et al., 2019). Failure to maintain indoor temperature and humidity within the limits defined by the lower and upper critical thresholds for different animal weights, can lead to heat stress and discomfort with significant reductions in growth rate, feed intake, and increased risk for respiratory and other diseases. Sufficient fresh air provision is critical not only to maintain animal hygiene but also avoid the exposure of workers to harmful gas emissions who are also vulnerable (Myer & Bucklin, 2001; Huynh, Aarnink, Truong, Kemp, & Verstegen, 2006; Santonja et al., 2017; Mikovits et al., 2019). To achieve the necessary level of control, farm managers often equip the pig housing facilities with state-of-the-art ventilation, heating and cooling systems. Because of the antagonistic nature of the ventilation and heating system operations, it is important that potential compromises are carefully assessed prior to the choice and implementation of specific technologies to avoid inefficient use of resources and potential financial losses through increased energy costs and reduced productivity (St-Pierre et al., 2003; Lammers et al., 2010b). In a typical European intensive pig farming system, as in the case of Denmark and Sweden, negative pressure ventilation systems are commonly implemented as a robust solution for fresh air provision against variability in outside wind intensity and direction (AHDB, 2016; Santonja et al., 2017; SEGES, personal communication; SLU, personal communication). When it comes to heating systems the options are many, but mainly categorised as solutions for zone heating or room heating. Floor heating or radiant heating from above the animals are two different systems for zone heating that is targeted to specific areas of the barn. These methods are quite effective when targeting the precise control of temperature at animal level, but can be costly (Lammers et al., 2010b). Pre-heating of incoming air or post-heating once the housing air has been fully refreshed are methods of room heating that are typically used to reduce costs (Lammers et al., 2010a; Lammers et al., 2010b; Santonja et al., 2017). Unless outdoor temperatures are very low (e.g. below 0 ℃), heating is mainly required for the first stages of a pig's life and is generally applied at the lactation production stage (piglets) and for the first two weeks of the nursery (smaller weaners) (Wellock, Emmans & Kyriazakis, 2003; Santonja et al., 2017; SEGES personal communication; SLU personal communication).

iii) ***The pens, including construction materials, bedding material & toys, and occupancy characteristics.***

Pen design varies across production stages in an integrated pig farming system, but also across different countries for the same production stages (Santonja et al., 2017; SEGES, personal communication). In European systems that adhere to strict regulations for improved animal welfare (Council Directive 2008/120/EC, 2008), it is typical to have relatively large space allocated per animal (i.e. 0.7 – 1.3 m^2 per fattening pig) and the provision of small amount of some material, usually straw, to serve as a toy for the animals (Mul, Vermeij, Hindle, & Spoolder, 2010). Pregnant sows at gestation are commonly kept in group housing, where a big T-shaped pen allows relative freedom and interactions between the animals (SEGES, 2012). The pens at lactation are designed mainly around the aim to minimise mortality, due to cases when a sow accidentally might roll over a suckling piglet, or get scared and tramp them (SEGES, 2017). Shelter-like constructions might be present many times at a nursery pen. Under that shelter, temperature is significantly higher than average room temperature. These shelters are used by the younger weaners to facilitate growth especially during the colder months (SEGES 2011a). Finally, at the fattening production stage the pen is defined as a plain construction with limited features; perhaps a small amount of bedding or toy material exist. The main concern during the fattening period is the management strategy followed when grouping the animals in pens. The grouping criteria is normally weight and special consideration is given in group dynamics to avoid aggressive behaviour (i.e. tail biting) that might hinder animal growth and reduce overall hygiene (SEGES, 2011b; Santonja et al., 2017, SEGES personal communication; Mul et al., 2010). In some countries where the annual average temperature is low (i.e. less than 10 °C), bedding material (commonly straw) can be found on the solid part of the floor, to help heat the animals without increasing costs for additional use of the heating systems (SEGES personal communication; SLU personal communication). In cases where pen fouling occurs (pigs dunging on the lying, solid area of the pen) and the bedding material is not changed often, ammonia emissions can largely increase (Aarnink & Elzing, 1998; Sommer et al., 2006; Santonja et al., 2017).

iv) ***Manure management at pig housing.***

Intensive pig production systems can be categorised in two main groups with regards to management of animal excretions: the ones based on slurry and those based on solid manure. The term slurry is used to describe the semi-liquid form of manure that contains both faeces and urine, and has not been dried out. Slurry based production systems are particularly popular because they allow for easier cleaning of the pens and therefore improved pen hygiene throughout the system. According to this approach, pig farming systems use partly slatted floors to let slurry fall through the dunging area and into a different compartment underneath the pen – the slurry pit. Slurry is stored in the slurry pits under the farm for lengths of time that vary among different pig farms, from a few weeks to a few months, before it is finally pumped out of the slurry pit and into the outdoor slurry storage (see next section *Manure management*) (Santonja et al., 2017; SEGES personal communication; SLU personal communication). The frequency of slurry removal from the slurry pits has significant effects on system environmental performance and animal health, since slurry is a great source of harmful emissions (i.e. ammonia) particularly when stored in relatively warm places (Aarnink & Elzing, 1998; Sommer et al., 2006; Rigolot et al., 2010; Santonja et al., 2017). Besides the environmental and animal welfare implications, slurry handling practices might have important consequences for farm profitability, as pen cleaning relies on manual labour (farm workers) and slurry removal is performed by pumping technologies that can incur high costs for their operation and maintenance.

Manure management

While part of manure management takes place at pig housing, the manure management component refers to practices for the storage of manure outside of the pig housing facilities, its treatment and disposal. To differentiate between the two, the thesis will generally refer to manure management at pig housing as “slurry handling”, while the more distinct component described here will be referred to as “manure management”.

In the manure management component of European pig farming systems, the storage, treatment and application stages are identified.

i) ***Manure storage***

In liquid slurry based pig farming systems across Europe, the most common storage method is in large, concrete or steel, covered or not, liquid slurry tanks that are above or below ground. Slurry is being pumped into the tanks using a slurry pumping system and pipes or a slurry tanker, and stored there for many months – nine month storage being the average duration for Denmark and Sweden (Ministry of Environment and Food of Denmark, 2017; Santonja et al., 2017). As mentioned above, slurry is a significant source of harmful emissions and therefore it is a good practice to cover the slurry tanks to minimise surface exposure to air. In Denmark and Sweden specifically, slurry tanks are above ground and covered by plastic roofs to also prevent rainfall from increasing slurry volume and costs of transportation during the application stage (Sommer et al., 2006; SEGES, personal communication; SLU, personal communication).

ii) ***Manure treatment and application***

Manure treatment primarily aims in reducing nitrogen and phosphorus losses from pig manure and therefore to improve its efficiency as organic fertiliser at the application stage. To achieve this, the farmer is usually required to implement some complex and often expensive technological system. For this reason, the only treatment practice implemented in the majority of pig farming systems across Europe is stirring (agitation) of the slurry before filling the tanks or discharging them, in order to obtain an evenly distributed nutrient mix in the fertiliser (Santonja et al., 2017). After treatment, manure is applied on fields as organic fertiliser for crop production. Pig farmers across Europe typically own some cropland where essential pig feed ingredients are grown, and so the direct benefits from manure application come in the form of discounts in the use of synthetic fertiliser (Nguyen et al., 2011; Santonja et al., 2017). In most cases, European Directives set guidelines and nutrient deposition limits that dictate the more appropriate land-spreading techniques and locations, taking into consideration manure composition, nature sensitive zones and areas vulnerable to specific nutrients, mainly nitrogen and phosphorus (Ministry of Environment and Food of Denmark, 2017). These are therefore important factors to account for when evaluating the sustainability of a pig farming system, especially when making decisions about optimal manure management strategies and overall farming system configurations. In cases where relevant agri-environmental policies force emission or nutrient deposition ceilings (e.g. Nitrates Directive), or where markets for renewable energy and enriched manure for organic fertiliser have created the need and conditions for treatment of manure after storage, farm managers have a range of alternative strategies in which they may invest (Hutchings, ten Hoeve, Jensen, Bruun & Søtoft, 2013; Ministry of Environment and Food of Denmark, 2017). The most commonly implemented of those for Europe are anaerobic digestion of slurry, acidification of slurry and separation of slurry (ten Hoeve et al., 2014; Santonja et al., 2017).

Anaerobic digestion

Anaerobic digestion takes place in specialised digesters – plants and can be performed under many different settings regarding temperature (e.g. mesophilic 30-45°C, thermophilic 50-55°C), hydraulic time retention, substrate (different ratios in the manure mix), co-substrate (e.g. grass silage, industrial waste) and other factors. Through the anaerobic digestion process, biogas and digestate are generated at rates and characteristics largely dictated by the conditions under which digestion happens (Triolo, Ward, Pedersen & Sommer, 2013; Vega, ten Hoeve, Birkved, Sommer & Bruun, 2014). The two most common paths for the biogas are either through a Combined Heat and Power (CHP) plant, or to be upgraded in biomethane and directly injected for use in the natural gas grid. The nutrient enriched digestate is typically applied using the same land-spreading methods as with raw slurry, but may require longer transportation distances to meet the nutrient deposition limits imposed by relevant policies to mitigate impacts on ecosystems (ten Hoeve et al., 2014; Santonja et al., 2017, SEGES, personal communication). The popularity of anaerobic digestion is increasing due to its large potential for renewable energy generation. In addition to on-farm digesters, a rapidly expanding strategy is the digestion at central facilities managed by groups of livestock farm managers, as in the case of Denmark (Al Seadi, 2017).

Slurry acidification

Slurry acidification is used to reduce ammonia emissions by decreasing the dissociation of ammonium ions (NH_4^+) (Fangueiro, Hjorth & Gioelli, 2015). The process of reducing slurry pH requires the addition of a strong acidifying agent, usually sulphuric acid (H_2SO_4), and can take place at all stages where manure is stored and processed. According to where slurry is acidified, it is defined as 'in-house acidification', 'storage acidification' and 'field acidification'. The sooner slurry is acidified (i.e. 'in-house acidification'), the more ammonia emissions can be avoided and higher amounts of NH_4^+ would be available at field application for crops. Aside from the benefits associated with reduction of ammonia emissions, slurry acidification can have adverse effects on pig health when performed in the slurry pits underneath the pens (Borst, 2001). This treatment method is commonly used in only a few countries across Europe, Denmark being one of them, due to its relatively high cost of implementation; generally economy of size applies in this scenario and slurry acidification is more cost-effective for the larger farms (> 750 sows) (Kai, Pedersen, Jensen, Hansen & Sommer, 2008; Birkmose & Vestergaard, 2013; Saue & Tamm, 2018; SEGES, personal communication).

Slurry separation

Slurry separation techniques have mainly been developed to facilitate nutrient re-distribution with the separate application of a liquid and a solid fraction, under different regimes and at different locations (ten Hoeve et al., 2014). Such solutions are particularly important when nutrient surpluses on farms lead to nutrient leaching, which is a big threat of pollution for surface and ground water bodies (Christensen, Christensen & Sommer, 2013). With the separation of slurry, the liquid fraction contains the bigger part of easily available nitrogen and so it can be used as a good nitrogen fertiliser, while the solid fraction is phosphorus rich and contains slowly available nitrogen so it is better valued as a phosphorus fertiliser. Furthermore, the solid fraction is a lot less voluminous than the liquid, and therefore allows for cost-efficient application far from the farm (ten Hoeve et al., 2014; SEGES, personal communication). While slurry separation is an effective strategy in controlling nutrient distribution, especially when a farm is located near nature sensitive and nutrient vulnerable zones, it does not help greatly to reduce important emissions such as ammonia and so other manure treatment options are often preferred over it (ten Hoeve et al., 2014; SEGES, personal communication).

Within the whole-farm, life cycle approach adopted throughout this thesis, special consideration is given to the pig housing and manure management components of the pig production system, including potential interactions between those. In this way, the thesis addresses a gap in literature by investigating the contribution of these components in system environmental impact. Furthermore, it evaluates potential environmental and economic consequences of modifications in these two components that aim to improve system environmental performance through mechanisms that were briefly described in the subsections above. Such interactions have often been ignored in studies that focused on pig farming system environmental performance, but are critical in guiding cost-effective investment decisions for the improvement of the pig production sector.

1.2. Sustainability assessment methods and application in pig production

Sustainability assessment methods aim to evaluate potential impacts that arise from a production system and are associated with all three pillars of sustainability: environmental, economic, social (Kebreab, 2013). Such tools are essential in achieving sustainable development at a system or broader level (i.e. sector) and when assessing the potential of technological innovations to help meet system sustainable development goals. Sustainability indicators and metrics also play a central role in conveying information to audiences of diverse background, as is often the case of policy makers and other stakeholders (Singh, Murty, Gupta & Dikshit, 2009).

In this thesis the environmental and economic aspects of sustainability in the pig production sector are focused. Trade-offs between these two sustainability pillars are evaluated when implementing alternative and novel management strategies. The following sections present the main principles and state-of-the-art specific to pig production for environmental life cycle assessment, life cycle cost analysis and discounted cash flow analysis, and environmental abatement cost analysis.

1.2.1. Environmental life cycle assessment (LCA)

In order to assess the environmental impacts of a pig production system, it is generally accepted that one of the most appropriate methodologies to follow is the LCA (McAuliffe et al., 2016; FAO, 2018b). LCA modelling provides a holistic, quantitative approach to the assessment of environmental impacts linked to product and processes over their lifetime (International Organisation for Standardisation – ISO, 2006; Lopez-Ridaura, Van der Werf, Paillat & Le Bris, 2009). In the case of pig production, pig meat is defined as a main product and slurry / manure as a by-product.

The environmental LCA methodology has been developed to address the following purposes: i) to help identify those components of the system that significantly contribute to system environmental impact and those that have the greatest improvement potential, ii) to help compare the environmental performance between different systems (supply chains) and different products, and iii) to help compare different scenarios for a single system (supply chain) and for a single product (Guinée, 2002; Finnveden et al., 2009; European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010). The outputs of an environmental LCA are easy to interpret and therefore make it a popular methodological option when performing sustainability assessments for a variety of sectors with the aim to convey information to stakeholders (Finkbeiner, Schau, Lehmann & Traverso, 2010; Guinée et al., 2011). The LCA methodology is widely applied by a variety of organisations besides academia, such as governmental authorities, public and private consultancies and other stakeholders in the industry (Rebitzer et al., 2004). For these reasons, the LCA methodology was selected in this thesis as a suitable method to evaluate strategies that promote a shift towards a more sustainable European pig production sector.

However suitable, LCA is one of many methodological approaches developed to evaluate the sustainability of supply chains such as pig production (Finnveden & Moberg, 2005). 'Risk assessment' is commonly used to estimate the adverse effects of emissions on ecosystems (Environmental Protection Agency, 1998). 'Environmental justice' tools also address issues related to high environmental impacts, for example due to intensified pig farming near nature sensitive areas, but focus on evaluating the sustainability of the communities at the receiving end of those impacts (Su et al., 2009). While these are useful tools in predicting the direction and magnitude of impacts on ecosystems, and to incorporate the perception of impacts associated with pig farming by stakeholders (i.e. local communities), they did not fit the purposes of this thesis that focuses more on identifying solutions on the production side (supply chain). The potential to integrate such methodological approaches along with the framework presented in this thesis is further discussed in Chapter 6.

According to the relevant ISO guidelines (ISO, 2006), four phases are identified in the development of LCA studies (Fig. 1.1).

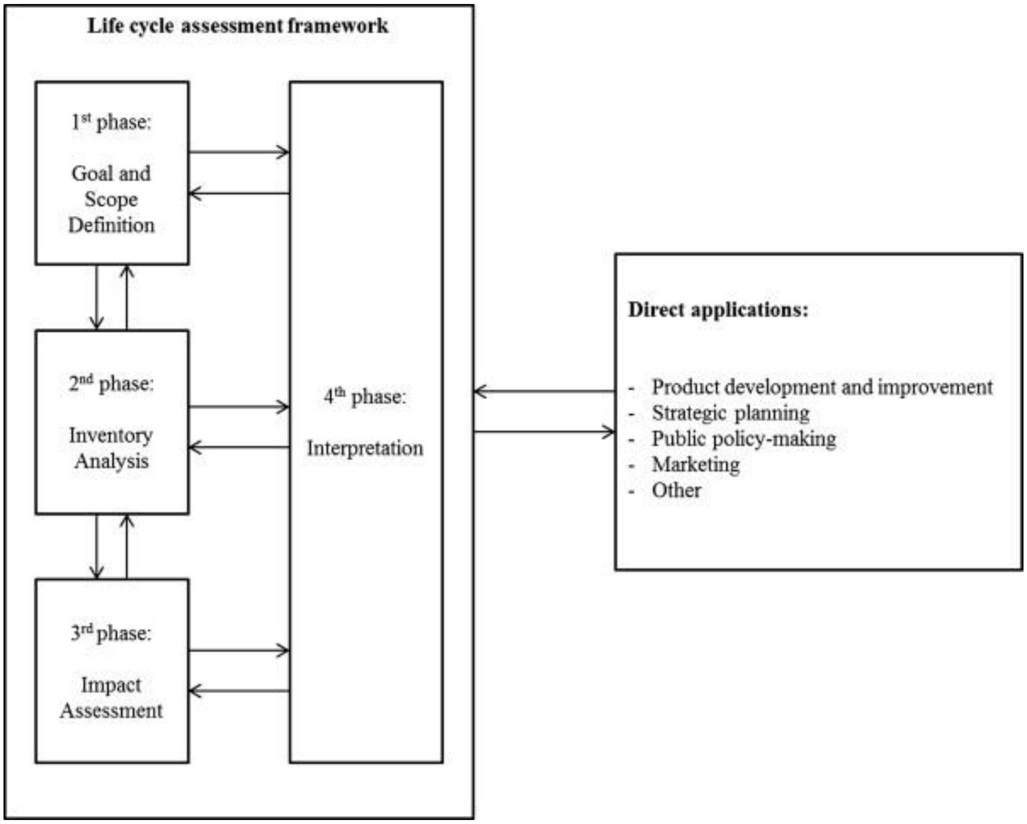


Figure 1.1: Four phases in the development of life cycle assessment studies according to the International Organisation for Standardisation – ISO guidelines (Source: Reckmann, Traulsen & Krieter, 2012)

Phase 1: Goal and Scope of Life Cycle Assessment

The most important step in performing an LCA study is the definition of its goal and scope, since these will dictate all important decisions along the development of the model, and also later facilitate interpretation of the conclusions (Guinée, 2002; Curran, 2017). At this phase, it is crucial to define the most fundamental elements of the LCA design: the purpose and application of the study (i.e. comparative LCA for environmental abatement scenario analysis), the stakeholders who will receive the outputs of the study (i.e. academics, policy-makers), the functional unit, the allocation method and the system boundaries.

The functional unit has a central role as it is used to quantify system performance in fulfilling a production cycle to deliver the specific amount of produce. In the case of this thesis, the functional unit is one kilogram of live weight (LW) pig at the farm gate, and therefore it is used to describe the amount of inputs are required for the pig farming system to produce this quantity. Functional units need to vary according to the purpose and application of the LCA study. Another common unit used on studies that focus on single livestock production systems is the ‘carcass weight' (or 'cold' weight) (Mackenzie et al., 2016). When different livestock systems are compared and depending on the focus of the study (i.e. whole-farm, manure management only) there is a need for more representative units that capture the common elements of their different outputs, such as 'mass of protein', 'energy content', 'mass of manure' and others (McAuliffe, Takahashi & Lee, 2020).

'Cradle-to-farm gate' and 'cradle-to-grave' are the most common system boundaries defined in LCA studies on livestock systems. In fewer cases, LCA models attempt to assess systems through a 'cradle-to-cradle' approach that aims to evaluate 'absolute sustainability' as opposed to 'relative' that is captured within the most common boundaries (Bjørn & Hauschild, 2013). Finally, according to the ISO guidelines for best practice in LCA, system expansion should be adopted whenever possible to include additional processes that are relevant to any by-products the system generates (ISO, 2006; Weidema & Schmidt, 2010). If system expansion is not feasible and an allocation method should be selected, then literature suggest that economic allocation should be preferred over methodologies that are based on physical properties and relationships, to avoid complications due to the complex mechanisms underlying interrelations between the various flows and processes (Mackenzie, Leinonen & Kyriazakis, 2017a).

Phase 2: Life Cycle Inventory Analysis (LCI)

In the second phase of the development, data describing all inputs and outputs relevant to the production process within the system boundaries is compiled. Although a straightforward procedure this can often be the most time-consuming step of the LCA study (Suh & Huppes, 2009). The specific data are characterised as 'foreground' and are usually obtained directly from the system under assessment, and 'background' that refer to processes which cannot be described with primary data within the scope of the study. The latter are usually acquired from large, detailed databases that focus on specific sectors, for example the 'AGRIBALYSE' and 'Agri-Footprint' databases for feed production related data (AGRIBALYSE, 2016; Agri-Footprint, 2017; Durlinger, Koukouna, Broekema, Paassen & Scholten, 2017), or the 'Ecoinvent' database with information on various emissions for example related to the production of construction material and transportation methods (Wernet et al., 2016). Due to the data intensive nature of LCA models, despite the data collection process being straightforward, this is also the phase associated with the main methodological limitations such as data gaps and missing information on data related uncertainties (Guinée, 2002; Mackenzie, Leinonen, Ferguson & Kyriazakis 2015).

Phase 3: Life Cycle Impact Assessment (LCIA)

As soon as all the required data has been collected in phase two, characterisation factors are applied relate any emission identified within the system boundaries to the any environmental impact they contribute. For example, CO_2 contributes to global warming potential and acidification of marine ecosystems and so it should be considered when evaluating either impact. These characterisation factors have been scientifically defined over years of measurements and experimentation, and are available in widely accepted and established impact assessment methodologies such as the 'CML' (Heijungs, Guinée & Huppes, 1997) and 'ReCiPe' (Huijbregts et al., 2017). Geographically relevant, spatially explicit characterisation factors should be used whenever possible to enhance accuracy of estimates (Bulle et al., 2019).

Phase 4: Interpretation

In the final phase of the LCA study, the data and model are tested for uncertainties and accuracy of estimates through statistical analysis, usually by performing multiple Monte Carlo simulations. Subsequently, a decision is necessary about how the specific outputs will be summarised, which should be related to the goal and scope defined in phase one. One common approach when the results are directed to policy makers is to report the outcomes without assigning any weights or aggregating across different impact categories assessed, therefore maintaining a more pragmatic and objective presentation. Any conclusions and policy implications can then be generated along with the stakeholders.

Attributional, Consequential, Integrated and Prospective LCAs

As the popularity of LCAs but also the complexity of questions regarding sustainability increased over the past few years, so have the different types of LCAs developed, expanding the methodological framework outside the established ISO and national (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010) guidelines (Guinée et al., 2018). Attributional LCAs and consequential LCAs are the most widely implemented types of LCA models. The first type is used to estimate environmental impacts associated with the life cycle of a specific product. The latter is associated with system boundaries that expand far from the supply chain of the specific product, and attempt to estimate direct or indirect impacts as a consequence of certain decisions, usually the change in demand of the product evaluated. Expansion of the system boundaries is also commonly adopted in attributional LCAs whenever possible, to enhance accuracy of estimates by capturing flows and impacts associated with any potential co-products. Such 'attributional-consequential hybrid' models are developed to help get the benefits of capturing processes that are indirectly associated with the supply chain under assessment, and avoid to reduce transparency of the study or largely increase uncertainties as is often the case with consequential LCAs (Curran, 2007).

Integrated LCAs combine the aspects of an LCA as described above with other modelling approaches including economic impact analysis, geographic information systems, climate change scenarios and many others. The LCA framework presented in Chapter 4 specifically could also be classified as a prospective LCA. Such models attempt to estimate future environmental impacts using future scenarios, such as the Representative Concentration Pathway (RCP) scenarios for climate change. The two latter types of LCA models, integrated and prospective, have not been widely applied in the livestock sector and especially pig production (Reckmann et al., 2012; McAuliffe et al., 2016)

Environmental Impact Categories

The main environmental impact arising from pig farming systems is associated with the production and management of manure. The amounts of nitrogen and phosphorus excreted in pigs manure are significant contributors to eutrophication of freshwater bodies and acidification of terrestrial ecosystems. Specifically, pig production exhibits some of the highest levels in the livestock sector for these environmental problems (de Vries & de Boer, 2010).

Adhering to the established guidelines for environmental impact and water footprint assessments of the pig supply chains, as established by the Livestock Environmental Assessment and Performance (LEAP) Partnership (FAO, 2018b; FAO, 2018c), the environmental impact categories described in the following paragraphs were evaluated in Chapters 2, 3 and 4 of the thesis, whenever environmental LCA models were applied.

Global Warming Potential (GWP) was considered throughout, using greenhouse gas (GHG) emissions as indicators within the system boundaries. GHGs form an atmospheric layer that captures energy emitted from earth that would normally escape into space, and return it back. Due to this mechanism they are the largest contributors to global warming (Dong et al., 2006) and have received the most attention in environmental impact assessment studies. In the assessment of GWP, CO_2 is used as the reference unit and so the potential of all other GHGs is measured in 'CO_2 equivalents' for a specified timescale (often 100 years), to facilitate interpretation of outputs and avoid confusion due to the different longevity and energy absorbing potential of different gases.

Aside from animal related emissions like methane (CH_4), GHGs can be released into the atmosphere when burning fossil fuel, therefore adding to climate change issues (Pittock, 2017). Therefore, monitoring non-renewable energy use (NREU) should not be neglected. Fossil fuel depletion is commonly measured in mega joules (MJ).

Next to GWP and GHGs, eutrophication is another significant environmental problem associated with pig production, particularly due to that it is aggravated by most nitrogen and phosphorus related emissions (Elser et al., 2007; de Vries & de Boer, 2010). Nutrient surpluses in freshwater bodies or coastal marine ecosystems from agricultural activities such as the application of manure and synthetic fertilisers in crop production, can cause large algal blooms. This creates a catastrophic chain reaction where sunlight is blocked by the surface algae making the underwater conditions adverse for other autotroph organisms that inevitably die and decompose; the increased decomposition depletes oxygen and in the end even the larger consumers (heterotrophs) cannot survive (Sharpley & Rekolainen, 1997; Correll, 1998). Eutrophication potential (EP), including freshwater eutrophication potential (FEP) and marine eutrophication potential (MEP), are commonly expressed in units of phosphorus (P) or nitrogen (N) equivalents according to which is the limiting nutrient, or often in units of phosphate (PO_4).

Acidification potential (AP) is another impact category largely affected by N-related emissions and in particular NH_3 and nitrous oxides (NO_x), is acidification of terrestrial (TAP) and aquatic (AAP) ecosystems. Other potentially harmful emissions that contribute to this category are sulphuric compounds like the sulphur dioxide (SO_2^-) and sulphuric acid (H_2SO_4) (Azevedo, van Zelm, Hendriks, Bobbink & Huijbregts, 2013a; Huijbregts et al., 2017). To avoid dramatically increasing AP when implementing acidified slurry as organic fertilizer, calcium carbonate ($CaCO_3$), which is alkalic, is commonly added in the slurry mix during the application process (ten Hoeve et al., 2014). Acidification potential is usually expressed in SO_2^- equivalents.

Non-renewable resource use (NRRU) has been taken into account in LCA studies more often than not, despite controversies regarding the different ways that have been proposed for its definition over the years. NRRU is measured in equivalents of antimony (Sb), but this is an area for debate since some studies state that there is no scientifically "correct" way to characterize abiotic depletion of resources. To date, the CML method is accepted and considered to be the most appropriate method for the assessment of NRRU (Van Oers & Guinée, 2016).

Following the ISO (2014) standards, a water footprint assessment can be performed within the frame of an environmental LCA to address potential impacts of water use (quantity), but not of the quality of available water resources. A more comprehensive method to address this gap, is based on the Available Water Resources (AWARE) measured in m^3 per unit of surface in a given watershed compared to the world average. To account for the potential to deprive another user of water, the method estimates the world average after human and ecosystem demands have been met (Boulay et al., 2018).

1.2.2. Economic impact assessment

Life Cycle Cost Analysis (LCC), Discounted Cash Flow Analysis (DCF) and Cost Benefit Analysis (CBA)

Life cycle cost analysis or life cycle costing (LCC) was first used back in the 60s' for the evaluation of investment choices for military equipment by the USA (Sherif & Kolarik, 1981), and later in the 70s' to inform policy making and business decisions in Europe (UNEP, 2011). Conventional LCC models in pig farming aim to address the economic consequences of the investment decisions made by a farm manager (Ness, Urbel-Piirsalu, Anderberg & Olsson, 2007). In the development of a life cycle based economic modelling approach all cost and revenue streams within the system boundaries are identified and subsequently linked to the best available financial information (Hunkeler, Lichtenvort, & Rebitzer, 2008; Stokes, Mullan, Takahashi, Monte & Main, 2020). Then they are usually discounted to present values over the time horizon (i.e. economic lifetime) through a Discounted Cash Flow (DCF) analysis, to allow for a more accurate assessment of those variables that vary over time. Although this approach is generally acceptable, it has some 'grey areas' such as the choice of discount rates, since in commercial business transactions high discount rates are applied to reflect decision makers' time preferences for projects that recoup investment costs more quickly. However, from a broader social perspective applicable to long term environmental investments, lower discount rates may be appropriate to avoid excessively discounting large costs on future generations (Weitzman, 1994; Hoogmartens, Van Passel, Van

Acker & Dubois, 2014). Another controversial area of this modelling approach is that it is generally based on economic or useful lifetime, which usually differs from the actual lifetime of a product or service. For example, a ventilation system might have a 25 year lifespan in terms of materials, but where technologies are rapidly advancing, investments encounter obsolescence risks that may reduce their useful life because they are superseded by superior products. Furthermore, conventional LCCs do not always include prospective end-of-life related costs (i.e. salvage value, cost of disposal) or environmental costs (e.g. taxes on CO_2 emissions) that are yet unknown, and therefore one may argue they do not always consider the entire life cycle of a product (Norris, 2001; Hunkeler et al., 2008). Environmental LCCs build upon the conventional LCCs in this regard, by including waste disposal costs and environmental taxes, thus completing the life cycle (Kloepffer, 2008). Discounting is not applied within an environmental LCC and all variables are assumed to remain constant over time (Hunkeler et al., 2008).

Cost Benefit Analysis (CBA) has been used to facilitate comparisons between different investment scenarios using comprehensive indicators such as the Net Present Value (NPV), Annual Equivalent Value (AEV) or the Internal Rate of Return (IRR), which will be described in the following section. A typical financial CBA considers only the discounted cash flows of the investor without taking into account any environmental or social externalities, and therefore would not be a complete, sufficient tool to evaluate the overall social sustainability of an enterprise (Pearce, Atkinson & Mourato, 2006). External costs however, remain costs to the society regardless of who pays for them and therefore, it is important that private CBAs consider them to ensure the business reaches a socially efficient output rate. Internalised costs due to environmental impacts were introduced in the concept of environmental CBAs, by monetizing (expressing in monetary value) the various impacts (Weidema, 2006). Although this method is attractive, it comes with fundamental difficulties, mainly due to variability and subjectivity in the valuation process. As the aim of social CBAs is to assign a price to a broad range of external (to a business) effects, it relies to the society to value potential impacts on its resources. Therefore, the price of a specific effect may vary greatly between groups in different social contexts, or of different and educational cultural backgrounds. It may also vary over time and depending on social trends present at the time of valuation. Such challenges may hinder the generation of conclusions and policy making (Gómez-Baggethun et al., 2014). Therefore, a private CBA focusing on the cash flows within the boundaries of a single business is often the preferred method when aiming to compare financial performance between businesses and scenarios for its operations.

Financial performance metrics

NPV is used to evaluate the profitability of a projected investment and represents the difference between the present value of all revenues (cash in-flows) and present value of all expenses (cash out-flows). The NPV of an investment is a function of the net cash inflows-outflows, the time horizon of the projection and the discount rate applied to the cash flows over this time horizon (Brent, 2009). If an investment exhibits positive NPV, then it means that it is a profitable option for the time period evaluated; a negative NPV on the other hand indicates higher cash outflows than revenues over time (Hoogmartens et al., 2014). Annual Equivalent Value (AEV), represents the annualised monetary returns of an investment and is derived by annualising NPV. Investments with higher AEV are generally preferred. This metric is particularly useful because it converts the NPV to an annuity equivalent that is more readily interpreted relative to the standard annual farm income measures. Consequently, the AEV facilitates more intuitive comparisons of the financial returns from investments that differ in scale, for example when comparing anaerobic digestion (large investment) to a manure scraping technology (small investment) as potential measures to reduce emissions from livestock systems. The final metric that will be presented in the following Chapters is the Internal Rate of Return (IRR), which represents the discount rate (%) for which the NPV of an investment is equal to zero. In some cases where two investments are compared, one might exhibit higher NPV but lower IRR than another, due to the profile of cash flows (including the capital costs) associated with their implementation. To avoid such confusion, the thesis selected AEV as the primary metric to present and compare the financial performance of potential environmental abatement strategies.

1.2.3. Environmental abatement cost analysis

Cost of abatement, expressed in monetary units (i.e. €) per unit of pollutant abated (i.e. ton of CO_2 equivalents), can be effectively used to evaluate the cost-effectiveness of potential environmental mitigation investments in reducing specific impact categories. The metric has been widely applied to investigated ‘win-win’ strategies in a variety of sectors, as it is particularly useful in integrating environmental and financial outputs in a single, easy to interpret score (Beaumont

& Tinch, 2004; Stokes, Hendrickson & Horvath, 2014). To further facilitate communication of information relevant to the cost of abatement when many and diverse strategies are evaluated at a time, the concept of environmental abatement cost curves has been introduced. One particular type, the Marginal Abatement Cost Curve (MACC), has been very popular as a policy making tool in the agricultural and energy sectors (Soloveitchik, Ben-Aderet, Grinman & Lotov, 2002; Kesicki & Strachan, 2011; Eory, Topp & Moran, 2013; Tomaschek, 2015). With this type of analysis the aim is to communicate information about strategies to control system emissions by either investing in environmental abatement technologies or by reducing their output – production. The curves present the cost associated with the last unit – marginal abatement – of pollutant mitigation, as presented in Fig. 1.2. (McKitrick, 1999; Kesicki & Strachan, 2011). Investigating scenarios of varied production intensity is outside of the scope of this study. Furthermore, due to large differences in abatement potential and targeted impact categories, presenting the marginal abatement cost was not considered to be the most suitable method for the specific objectives of the thesis. An adapted MACC approach was followed instead, by presenting information about the total abatement potential achieved by a potential investment on one axis (i.e. width of bars in a graph) and the cost of abatement per unit of pollutant on the other axis (i.e. height of bars in a graph). Technologies are ranked in order of cost-effectiveness from left to right, which makes the task of identifying the most optimal solutions easier for the policy maker.

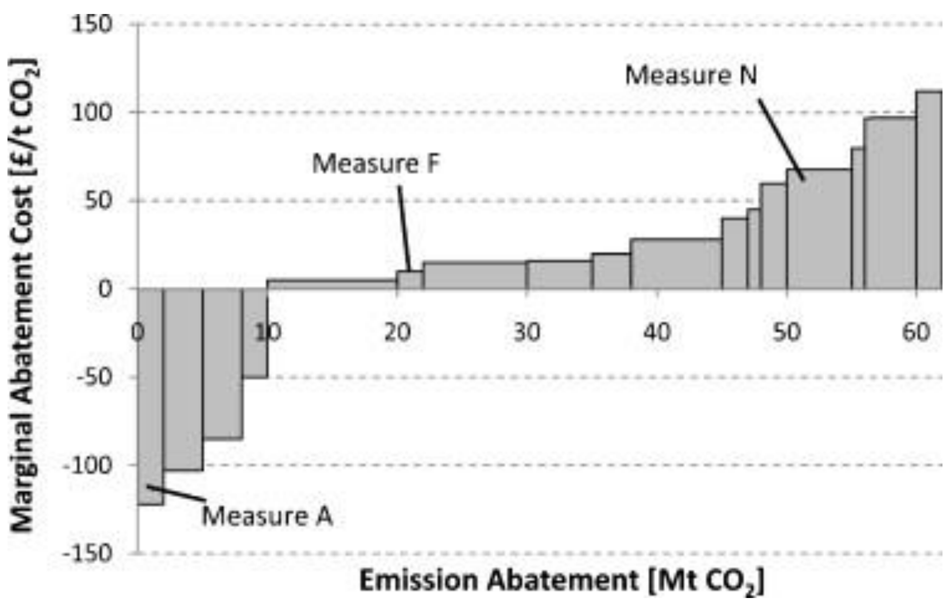


Figure 1.2: Example of a marginal abatement cost curve for the mitigation of carbon dioxide emissions (CO_2). (Source: Kesicki & Strachan, 2011)

1.3. Methodological challenges of life cycle based, sustainability assessment methods

When aiming to evaluate the sustainability of complex supply chains as in the case of pig production and other agricultural systems through a whole-farm, life cycle perspective, the practicioner will unavoidably face many challenges and limitations. First and foremost, due to the data intensive nature of such methods the majority of data inputs (LCI) are highly variable and often associated with large uncertainties. It is crucial that these uncertainties are addressed thoroughly to enhance accuracy of the model estimates (Groen, Heijungs, Bokkers, & de Boer, 2014a; 2014b). Additionally, in the case of comparative sustainability assessments it is particularly important to distinguish between data and model uncertainties, as well as between uncertainties specific to a scenario or shared between the different scenarios compared (Mackenzie et al., 2015). One popular method to overcome such limitations and address the issues of uncertainty is by performing multiple Monte Carlo simulations (Leinonen, Williams, Wiseman, Guy & Kyriazakis, 2012; Mackenzie et al., 2015). The thesis presents and applies this approach throughout, whenever environmental LCA models are presented (Chapters 2 through 5). Furthermore, the thesis attempts to address specific uncertainties related to geographic variability and projected climate change, with the development of integrated, life cycle based, sustainability methods that combine environmental and economic models with geospatial data and methods, as well as scenarios on future climate change (Chapters 4 and 5).

Another limitation associated with life cycle assessment methods is the issue of allocation regarding the environmental impact of each output of the system. As mentioned in *'Phase 1: Goal and Scope of Life Cycle Assessment'* of section 1.2.1. above, system expansion should be preferred and adopted whenever possible, to include additional processes, flows and impacts associated with potential by-products generated along the supply chain (Mackenzie et al., 2016). A big debate has been raised in literature to provide answers for the most appropriate allocation method when system expansion cannot be performed, however without reaching a definitive solution to date (Ekvall & Finnveden, 2001; Guinée et al., 2011; Mackenzie et al., 2016).

Potential challenges are even greater and harder to overcome when attempting to address the economic aspect of sustainability. While the practitioner may acknowledge and address uncertainties on the environmental side, up to date datasets on system financial performance are far more limited. This is mainly due to privacy concerns from the stakeholders and the importance to maintain market competitiveness. As a consequence, projecting financial performance in the future within the context of sustainability assessments is often hard, especially when aiming for highly accurate and certain estimates (Eory, Topp, Butler & Moran, 2018).

The individual studies of this thesis consider such methodological challenges in the development of environmental and economic life cycle models. Whenever possible, the thesis attempts to overcome specific limitations using comprehensive datasets and innovative methodological approaches to address potential uncertainties. By developing alternative scenarios for several of the pig farming system components and expanding system boundaries to encompass processes relevant to those scenarios, the thesis aims to enhance accuracy of predictions regarding the environmental and economic performance of the pig production sector, and to provide recommendations for potential strategies that could help improve pig farm sustainability.

1.4. Thesis aims

The overarching aim of this thesis was to evaluate the environmental and economic performance of representative European pig farming systems in a quantitative manner through the development of a novel life cycle based integrated framework, and identify potential strategies related to their pig housing and manure management components that aim to improve system sustainability.

To achieve this aim, the thesis first develops individual environmental LCA and economic models, which form the core of a whole-farm environmental abatement cost framework. The framework is further enhanced with the integration of a projected climate change scenario and a spatially explicit environmental analysis.

The individual Chapters of the thesis present the specific objectives targeted to achieve the primary aim:

Chapter 2: Aims to develop a whole-farm environmental life cycle assessment model, and evaluate the potential environmental implications of modifications in pig housing and manure management (identification of potential environmental impact hotspots).

Chapter 3: Aims to further develop the environmental LCA model into a whole-farm environmental abatement cost framework, and evaluate the cost-effectiveness of selected farm investments with environmental impact abatement potential.

Chapter 4: Aims to investigate the environmental and economic consequences of the implementation of pig-cooling strategies that aim to mitigate pig farm environmental impact, by expanding on the whole-farm environmental abatement cost framework with the integration of a projected climate change scenario analysis.

Chapter 5: Aims to investigate the effect of spatial variability on the cost-effectiveness of selected farm investments with environmental impact abatement potential, by further developing the environmental abatement cost framework with the integration of a spatially explicit environmental LCA analysis.

This thesis demonstrates the effectiveness and importance of comprehensive assessments that evaluate the performance of a pig farming system both from an environmental and an economic perspective. In Chapter 2, it addresses the need to evaluate system environmental impacts through whole-farm approaches that account for potential interactions between the different system components. In doing so, it develops and applies a whole-farm, environmental life cycle model for the investigation of impacts associated with a range of modifications in pig housing and manure management, while considering potential interactions between these two system components. In Chapters 3, 4 and 5, the thesis exhibits the capabilities of such models to assess the cost-effectiveness of farm investments that aim to mitigate system environmental impact and facilitate decision making for sustainable solutions, when integrated with financial, climatic and spatially explicit analyses. Finally, the thesis acknowledges important sources of uncertainty in the development and application of whole-farm sustainability assessment methods, particularly relating to climate change (Chapter 4) and spatial variability (Chapter 5). It attempts to address such uncertainties by developing and applying a novel, integrated framework that combines environmental LCA models, financial performance indicators, projected data on climate change and geographic information system (GIS) analysis methods. For reasons described in the Introduction the thesis, the specific EU cases of Danish and Swedish pig production were used as case studies to develop and test these novel environmental and economic impact assessment methods.

The contribution and potential benefits of this thesis are multi-fold and the intended audience diverse. LCA practitioners could benefit from the methodological advancements the thesis presents, particularly in facilitating interpretation and communication of complex environmental and economic life cycle assessments. The framework presented here can serve as a building block for on-farm decision support systems, helping farm managers explore the cost-effectiveness and environmental performance of potential on-farm investments, therefore improving farm sustainability. Finally, the specific results of this thesis can be used to inform policy making and guide decisions that may support the adoption of novel management practices that could improve sustainability of the agri-food sector.

Chapter 2. Environmental impacts of housing conditions and manure management in European pig production systems through a life cycle perspective: A case study in Denmark

Abstract

The potential of modifications in the housing conditions and manure management to reduce the environmental impact of a European pig production system were evaluated. The study was carried out using a cradle-to-farm gate life cycle assessment (LCA), with a functional unit of 1 kg of live weight pig at farm gate. The study used Danish pig systems as a case in point, with data provided by the Danish Pig Research Centre (SEGES).

Potential environmental impact hotspots at pig housing and manure management were identified through a local sensitivity analysis. A set of pig housing and manure management alternative scenarios were analysed using parallel Monte Carlo simulations, to quantify interactions between these two components of the system. The manure management scenarios were slurry acidification, screw-press slurry separation and centralised anaerobic digestion of slurry. The pig housing scenarios were constructed around variations of the following factors: i) level of barn insulation, ii) indoor temperature, iii) ventilation efficiency, iv) level of slurry dilution and v) frequency of slurry removal from barn pits.

Anaerobic digestion significantly reduced the environmental impact for Non-Renewable Resource Use (-34.1% compared to baseline), Non-Renewable Energy Use (-40.1%) and Global Warming Potential (-9.20%). Slurry acidification led to significant reductions in Acidification (-28.1%) and Eutrophication Potential (-14.2%). Slurry separation significantly reduced only Non-Renewable Energy Use (-2.26%).

The scenario analysis showed that the environmental performance of all manure management alternatives was affected by variations in all housing related factors, except for indoor temperature. The largest improvement in environmental performance of the manure management component was achieved for Acidification Potential (-5.51%) by increasing the level of slurry dilution under baseline manure management conditions. Slurry acidification was the least sensitive manure management alternative to modifications in pig housing. Both manure management and housing conditions have the potential to reduce the environmental impact of pig systems in Europe.

2.1. Introduction

Pig production systems are contributors to environmental impacts arising from livestock. On a global scale, pig production related greenhouse gas (GHG) emissions are about 700 million tonnes of CO2 equivalents annually (Macleod et al., 2013). Although significantly lower than emissions from beef and bovine dairy production (combined: 4623 million tonnes CO2 equivalents per year), increasing demand for pork meat and greater public awareness regarding GHG emissions from livestock systems, mean the carbon footprint of its production cannot be disregarded (Opio et al., 2013). Besides global warming, pig production is also regarded to be among the highest contributors to eutrophication of fresh water bodies and acidification of ecosystems (De Vries & De Boer, 2010).

Evidence suggests a need to evaluate the environmental consequences of pig production systems through a whole farm perspective, considering the impacts of alternative management practices across all components of the system (Petersen et al., 2007; Prapaspongsa, Christensen, Schmidt & Thrane, 2010a; Prapaspongsa, Poulsen, Hansen & Christensen, 2010b). Feed production is the largest contributor to environmental burdens from pig systems causing up to 65% of its global warming potential (GWP) (Basset-Mens & Van der Werf, 2005; Nguyen et al., 2011; Mackenzie et al., 2016). However, pig manure management is also a significant source of GHGs accounting for 18% of the total emissions from the livestock industry globally. Although technologies that target the reduction of emissions associated with pig manure management are currently applied, assessing and improving their effectiveness is important (Dennehy et al., 2017).

Slurry acidification is a common method applied in Danish pig production, through which farm managers can decrease NH3 and GHG emissions to a great extent. The largest reductions have been reported when acidification takes place before the outdoor manure storage stage (Hou, Velthof & Oenema, 2015; Ten Hoeve, Gómez-Muñoz, Jensen & Bruun, 2016).

The mechanical separation of slurry by screw press is another popular treatment method. The process returns a liquid and a less voluminous solid fraction of slurry and enhances nutrient re-distribution with the application of the solid, phosphorus rich fraction in distant farms while reducing fuel consumption during manure transportation (Ten Hoeve et al., 2014).

Anaerobic digestion of manure is rapidly expanding across Denmark; it has supported a 40 – 45% increase in Danish biogas production during 2016 – 17 (Al Seadi, 2017). The co-digestion of manure helps reduce nitrogen related emissions and produces a digestate with improved fertilizer characteristics compared to the untreated manure (Hjorth et al., 2009; Hamelin, Wesnæs, Wenzel & Petersen, 2010; Evans et al., 2018). Anaerobic digestion of pig manure has been previously reviewed (Hamelin et al., 2010; Vega et al., 2014), but only a few studies have considered the system from a whole – farm perspective (Cherubini, Zanghelini, Alvarenga, Franco & Soares, 2015; Dennehy et al., 2017).

While the above technologies are effective in reducing emissions associated with pig manure, their performance is directly related to the chemical composition and other properties of the manure (i.e. density). Various factors at pig housing can affect these characteristics and so the interactions between the housing and manure management components should be considered when assessing the environmental performance of a pig production system. Modifying indoor climate regulation parameters like the ventilation rate and indoor temperature can affect NH3 emissions from pig slurry at pig housing and impact the on-farm energy consumption. Variations in slurry handling practices at pig housing like the level of slurry dilution and the frequency of slurry removal from the barn pits can significantly affect manure chemical composition mainly through the reduction of NH3 emissions (Génermont & Cellier, 1997; Rigolot et al., 2010; Jarret, Martinez & Dourmad, 2011). Other pig housing characteristics like the level of barn insulation, barn and pen dimensions and construction material used, have the potential to affect the system environmental impact directly through changes in on-farm energy use and indirectly through the environmental impacts linked to the production of the construction material used.

Therefore, to evaluate the environmental impact of pig production systems we need to adopt a whole – farm perspective and account for the great diversity in farm management practices, housing configurations and manure treatment technologies.

The aim of this study was to evaluate the environmental performance of pig production systems through a holistic approach and to quantify the effect of variations in pig housing and manure management on system environmental impact, while accounting for any interactions between these two components of the system. This aim was addressed through the development of a detailed life cycle assessment (LCA) model within a global framework. The specific objectives of the study were:

1. To identify environmental impact hotspots associated with the pig housing and manure management components of pig production systems.

2. To assess the abatement potential of modifications in pig housing, while accounting for interactions with different manure management strategies.

2.2. Materials and Methods

The following sections provide a description of the methodological steps followed to achieve the aim and objectives of this study (Fig. 2.1).

First, an LCA model was developed to assess the environmental impact of the baseline scenario, while accounting for any data and model related uncertainties using multiple Monte Carlo simulations.

Then, potential environmental impact hotspots associated with the pig housing and manure management components of the system were identified, through a local sensitivity analysis.

Further, a set of pig housing and manure management scenarios were identified based on evidence from literature suggesting they can potentially affect the pig system environmental performance. The abatement potential of the different housing and manure management strategies was evaluated through an alternative scenario analysis, while accounting for their interactions and any uncertainties.

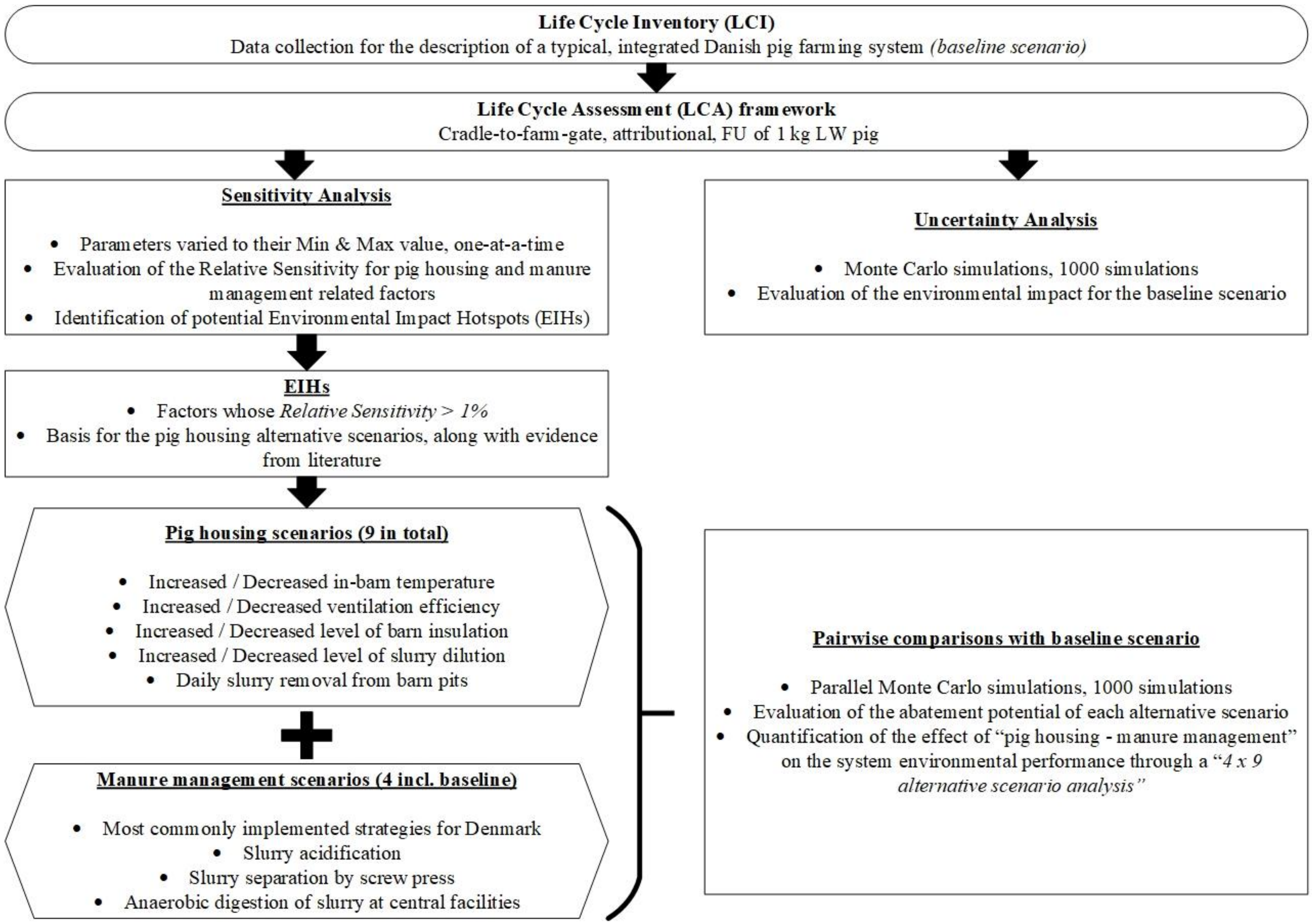


Figure 2.1: Schematic synopsis of the methodological steps followed for this study.

2.2.1. Pig farming system description
Geographical area

A representative Danish pig production system was purposefully selected, as a reference case study of European pig production. The choice was based on: i) good quality and easily accessible data (Danish Pig Research Centre, SEGES) and ii) homogeneity of the pig production systems across the country. The baseline scenario in this study, also referred to as average Danish pig production system, was characterised according to published statistical reports (Poulsen, 1998; SEGES, 2011a, 2011b, 2012, 2017) and expert opinion (personal communications with the researchers Mr. Finn Udesen, Mr. Kent Myllerup, Mr. Per Tybirk from SEGES).

Baseline scenario

The system under analysis was an indoor, mechanically ventilated, integrated Danish pig farm. A herd of 500 sows that followed a three-week batch farrowing system was modelled. The animals were offspring of Danish Landrace × Yorkshire sows and Duroc sires. For the description of the herd, data provided by SEGES were used to represent typical Danish pig farms; the average was adopted from the range of herd performance, weighted by the number of pigs per farm (Table 2.1). The LCA modelled four distinct production stages: gestation (gestating sows), farrowing (lactating sows and suckling piglets), nursery (weaners up to 30kg) and growing/finishing (pigs until slaughterweight and replacement gilts). The Appendix contains a detailed description of the production stages. The Life Cycle Inventory (LCI) described the following components of the pig production system: i) feed production, ii) animal production, iii) pig housing and iv) manure management (Section 2.4). Fig. 2.2 presents the system boundaries and main components of the model.

Table 2.1: Herd performance characteristics describing the baseline scenario, in the average, integrated Danish pig farm (data provided by the Danish Pig Research Centre, SEGES). C.I = confidence interval, NA = not available.

Parameter	Units	Mean value	Min 95% C.I	Max 95% C.I
Duration gestation	Days	116	114	118

Duration farrowing	Days	31.0	28.0	32.0
Duration early nursery	Days	28.0	26.0	30.0
Duration nursery	Days	21.0	20.0	22.0
Duration growing	Days	42.0	40.0	44.0
Duration finishing	Days	42.0	40.0	44.0
Litter size	Number of piglets	18.0	16.0	20.0
Litters per year	Number of litters	2.27	NA	NA
Birth weight	kg	1.35	1.30	1.40
Early nursery starting weight	kg	6.70	6.50	7.00
Nursery starting weight	kg	15.0	13.8	16.0
Growing starting weight	kg	30.0	28.0	32.0
Finishing starting weight	kg	65.0	63.0	66.0
Slaughterweight	kg	110	108	112

Gilt ending weight	kg	143	140	146
Sow mortality after birth	%	2.00	NA	NA
Sow replacement rate (annually)	%	50.0	NA	NA
Still born	%	21.3	NA	NA
Mortality at farrowing (suckling piglets)	%	13.0	12.8	13.1
Mortality at nursery (weaners)	%	3.10	3.03	3.16
Mortality at growing/finishing	%	3.30	3.23	3.37

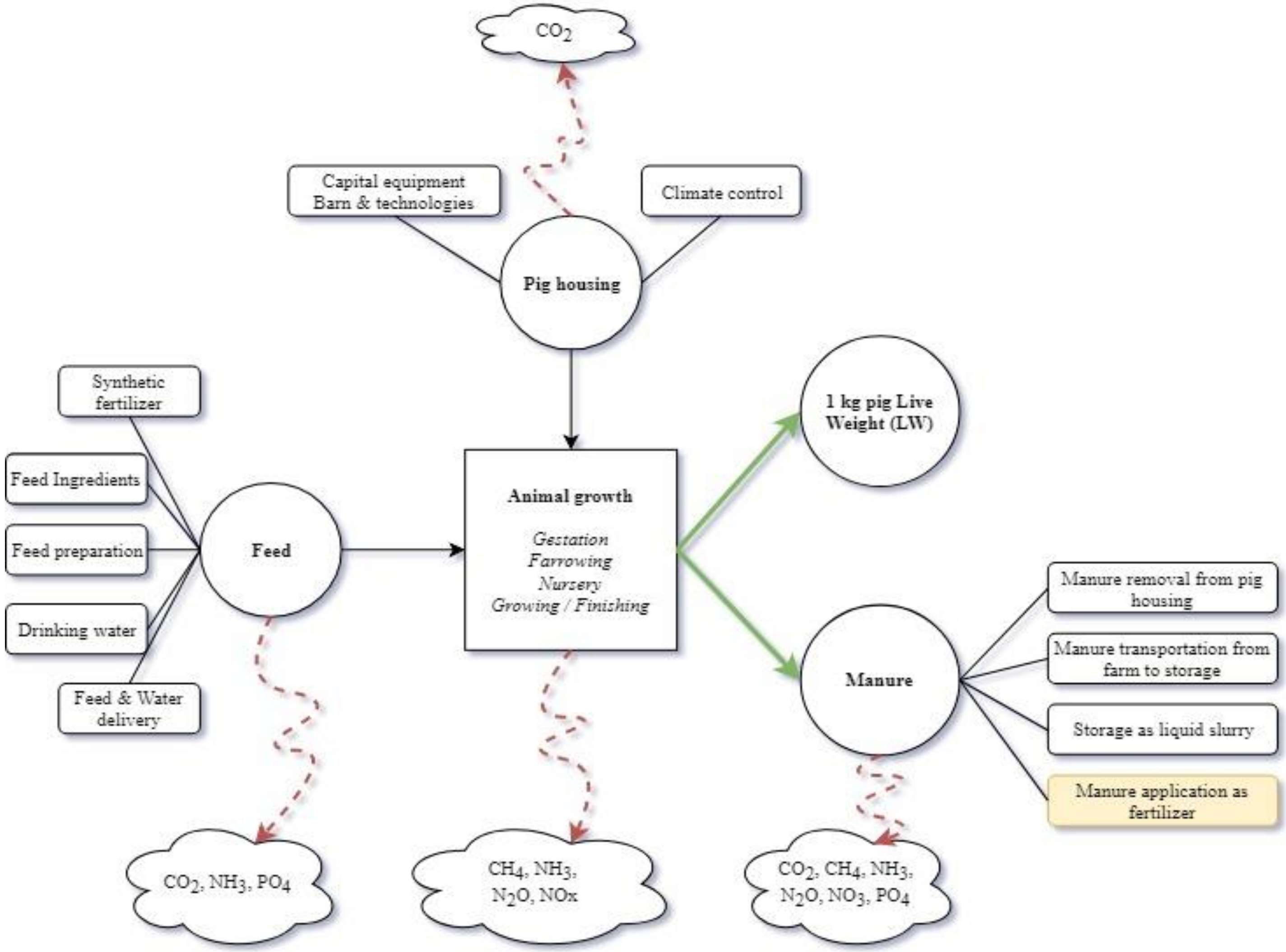


Figure 2.2: Schematic representation of the main components and flows of the basic LCA model. Black lines and arrows = input flows to main components of the model: feed, animal growth, pig housing and manure management. Green arrows = outputs of the system. Red arrows = emissions associated with main components. Yellow box = discounts in the form of avoided product. We considered the energy use (electricity, natural gas, diesel fuel) in all processes within the system boundaries.

2.2.2. Goal and scope of life cycle assessment

The assessment was carried out using an attributional, cradle-to-farm gate LCA model which was constructed in SimaPro 8.5.0.0 (PRé Consultants, Amersfoort, The Netherlands).

The Functional Unit (FU) was the production of one kilogram of live weight pig (1 kg LW) at the farm gate, including culled sows. System expansion was used to avoid co-product allocation, whenever it was necessary and possible. When this was unavoidable, economic allocation was used (Weidema & Schmidt, 2010; Mackenzie et al., 2017a). In this study, the pig production system was assumed to be a landless unit (Nguyen et al., 2011). A Monte Carlo approach (1000 simulations) was applied for the quantification of potential uncertainties associated with data inputs in the model (Mackenzie et al., 2015).

Life Cycle Impact Assessment (LCIA)

The CML-IA Baseline (version 3.05) methodology was adapted, with a focus on five midpoint impact categories as proposed by the FAO guidelines for environmental impact assessment of pig supply chains (FAO, 2018). Due to data limitations, land occupation and a water footprint assessment were not considered. The impact categories under assessment were:

Non Renewable Resource Use (NRRU) expressed in kg of antimony (Sb) equivalents.

Non Renewable Energy Use (NREU) expressed in megajouls (MJ).

Global Warming Potential (GWP) expressed in kg of carbon dioxide (CO_2) equivalents.

Acidification Potential (AP) expressed in kg of sulphate (SO_2^-) equivalents.

Eutrophication Potential (EP) expressed in kg of phosphate (PO_4^{3-}) equivalents.

2.2.3. Life Cycle Inventory (LCI)

Feed production

Six diet formulations were used across the production stages. These were constructed according to Tybirk, Sloth, Kjeldsen, & Shooter (2016) and Tybirk (personal communications, February 27, 2018) (Table A.21). The environmental impacts associated with the production of the individual feed ingredients including mineral supplements and synthetic amino acids were considered using the Agri-footprint and Agribalyse v1.3 databases (Colomb et al., 2013; Vellinga, Blonk, Marinussen, Van Zeist & Starmans, 2013; AGRIBALYSE, 2016; Agri-footprint, 2017).

Feed was assumed to come in pelleted form and purchased entirely from compound feed manufacturers; home – mixing was not simulated (Per Tybirk, personal communications, February 27, 2018). Energy use for pellet production and preparation processes (drying, grinding etc.) was adapted from Mackenzie et al. (2016).

Drinking water consumption was modelled according to recommendations for livestock welfare (DEFRA, 2013). The nutrient characteristics for each diet formulation were calculated according to Sauvant, Perez & Tran (2002), as presented in Table A2.2.

Animal growth

Methane (CH_4) emissions and nutrient excretion (N, P, K) linked to animal growth were calculated according to the mass balance principle, across the various developmental stages. The IPCC guidelines were used to account for nutrient retention rates (Table A2.3) and methane emission factors (Table A2.4) (Dong et al., 2006; Sommer et al., 2006; Tybirk, 2017). Animal-performance was assumed to be unaffected by the scenarios investigated; feed intake, weight gain and activity levels were not affected by changes implemented at pig housing, as the variations considered for indoor climate were maintained within the animals' comfort zone.

Pig housing: barn design and indoor climate

Four separate barns that house animals in the different production stages were considered: gestating barn, farrowing barn, nursing barn and growing/finishing barn. A detailed description of the building and indoor climate conditions for each can be found in the Appendix. Under baseline conditions, all barns were described as concrete, well-insulated constructions, with partially slatted concrete floor, under-barn slurry pits and mechanical ventilation. Barn dimensions and various materials used in its construction for each production stage (e.g. concrete) were considered. The study accounted for environmental impacts associated with the production of the individual materials required for the construction of the pig housing component using the Ecoinvent 3 database (Wernet et al., 2016).

The climate control system was modelled using the sensible heat balance principle $S_A + S_B + S_V = 0$, where S_A is the sensible heat release from the animal, S_B the sensible heat loss due to transmission through the building and S_V the sensible heat flow due to the ventilation system (Schauberger, Piringer & Petz, 2000). Energy demands for indoor climate regulation were calculated, while accounting for the interrelations between energy consumption and pig housing related parameters. Table 2.2 presents the main variables that describe the pig housing system under baseline conditions.

Due to data limitations on degradation rates specific to each component of the housing system, all parts of the basic building structure were assumed to have the same lifetime (50 years), although it is appreciated that certain parts need to be replaced sooner than others (e.g. floor slats). The same assumption was applied for the indoor climate control equipment (e.g. ventilation system, heating system) with a technological lifetime of 20 years.

Table 2.2: Main variables describing the housing system for the different animal stages in an average Danish pig production system. C.I = confidence interval, T = temperature, l = barn length, w = barn width, h = barn height.

Variable	Unit	Mean value	Min 95% C.I	Max 95% C.I
Outside T° Denmark	°C	7.70	2.58	12.8
T° gestation	°C	17.0	15.0	18.5
T° farrowing	°C	19.5	18.5	20.5
T° nursery	°C	20.1	17.0	24.0
T° growing/finishing	°C	17.5	15.0	20.0
Barn dimensions gestation (loose housing)	m (l * w * h)	44.0 * 25.0 * 2.70	42.0 * 23.0 * 2.20	46.0 * 27.0 * 3.30
Barn dimensions farrowing	m (l * w * h)	25.0 * 18 * 2.70	24.0 * 17.0 * 2.20	26.0 * 19.0 * 3.30
Barn dimensions nursery	m (l * w * h)	36.0 * 22 * 2.70	34.0 * 20.0 * 2.20	38.0 * 24.0 * 3.30

Barn dimensions growing/finishing	m(l * w * h)	36.0 * 22 * 2.70	34.0 * 20.0 * 2.20	38.0 * 24.0 * 3.30
Barn wall thickness	m	0.100	0.0800	0.120
Animal places gestation unit (sows)	Number of animals	500.	350.	650.
Animal places farrowing unit (sows)	Number of animals	83.0	58.0	108.
Animal places nursery unit	Number of animals	1,000	700.	1,300
Animal places growing/finishing unit	Number of animals	1,000	700.	1,300
Barn lifetime (building)	Years	50.0	20.0	80.0
Technological lifetime	Years	20.0	14.0	26.0

Manure management: at pig housing, storage and field

Methane (CH_4), ammonia (NH_3), nitrous oxide (NO_x), nitrogen (N_2) and dinitrogen monoxide (N_2O) emissions associated with manure at housing, storage and field application levels, were estimated.

Slurry removal from the barn pits and dilution of slurry, were the main slurry handling practices that took place at pig housing. Removal of slurry on a monthly basis was assumed (F. Udesen, personal communication, February 27, 2018). Slurry dilution under baseline conditions was described by a total ammoniacal nitrogen (TAN) concentration in slurry of 80%.

Upon removal, the slurry was stored in an outdoor, concrete, covered tank for an average of nine months (Sommer et al., 2006; Nguyen et al., 2011).

Field application was performed by trail-hose tanker (surface application) (Dong et al, 2006; Nguyen et al., 2011; Plejdrup & Gyldenkærne, 2011). According to Danish regulations, the substitution rate in the use of synthetic fertiliser was 75.0% for Nitrogen. A substitution rate of 97.0% for Phosphorus to account for potential leaching and 100 % for Potassium was assumed (Nguyen et al., 2011). Factors specific to emissions from manure storage and field application under baseline conditions are presented in Table A2.4.

2.2.4. Sensitivity analysis

A modified one-at-a-time, local sensitivity analysis was implemented to identify potential environmental impact hotspots in Danish pig production systems (Chiu & Lo, 2018). The analysis was performed for all impact categories on pig housing and manure management related parameters of the baseline scenario, as this was the core focus of this study. Table A2.5 lists the parameters included in the sensitivity analysis, along with the main characteristics of their associated distributions. In cases where data were not available, the distribution was assumed to be normal with the observed mean and standard deviation equal to 10% of the mean (Groen et al., 2014a; 2014b). These variables were tested to their ± 95% confidence intervals to estimate their sensitivity ratios (SR) from Equation 2.1 below. Absolute minimum and maximum values for each parameter were used when this was the only available information (triangular distribution). Whenever relationships between variables were not strong enough to build correlations in the model directly, variable independence was assumed (uncorrelated and independent) (Mackenzie et al., 2015). Equation 2.1:

$$(\mathbf{Eq.\,2.1})\; SR = \left| \frac{\left(\frac{Final\ result - Initial\ result}{Initial\ result}\right)}{\left(\frac{Min.\,or\ max.\,parametre\ value - Mean\ parametre\ value}{Mean\ parametre\ value}\right)} \right|$$

Initial result = model outcome with mean parameter value

Final result = model outcome with minimum / maximum parameter value.

The relative sensitivity of each parameter was calculated by dividing its largest SR value by the overall variation caused in the outcome by all the examined factors (cumulative sensitivity). When a parameter exhibited relative sensitivity greater than 1%, it was considered as a potential environmental impact hotspot.

2.2.5. Alternative scenarios description

Manure management alternative scenarios

In addition to the baseline scenario, the environmental performance of the following three alternative manure management strategies was evaluated. The scenarios chosen represent the most commonly used manure management alternatives in Denmark (F. Udesen, SEGES, personal communication, February 27, 2018). These alternatives aim to reduce GHG emissions at storage and field application, improve the properties of manure as a replacement for synthetic fertiliser in crop production and can help enhance nutrient redistribution.

Slurry acidification

Acidification was considered as an automated process that occurred in an acidification plant adjacent to the pig housing facilities. Slurry from the pits under the barn was pumped to the acidification plant where it was acidified, mixed and then pumped back to the under-barn slurry pits. The acidified slurry was stored and applied under baseline conditions (Kai et al., 2008; Fangueiro et al., 2015). The main inputs identified for this process were the addition of 9.7 kg highly concentrated sulphuric acid (96% H_2SO_4) and 15 kg of calcium carbonate ($CaCO_3$) per tonne of slurry acidified, as well as an additional 3 kWh per m^3 of slurry acidified of energy required for the mixing (Pedersen, 2004; Ten Hoeve et al., 2016).

Screw press slurry separation

Slurry separation by screw press is among the most commonly implemented manure treatment methods due to its low cost (F. Udesen, SEGES, personal communication, February 27, 2018). The separation process was assumed to occur at the manure storage level. The liquid fraction was stored on farm and applied to land in close proximity (~8km) while the solid fraction was transported and applied further from the farm (~100km) and with a different method (broadcast spreading and rapid incorporation). The substitution rate for N was different for the two fractions with Nliquid: 75% whereas Nsolid: 65% (Ten Hoeve et al., 2014).

Centralised anaerobic digestion

After a pre-storage stage of 10 days on farm, the co-digestion of pig slurry with industrial organic waste (80:20 w/w) was simulated, at a centralised plant (6 km from farm) for biogas production. The biogas was upgraded to bio-methane with the removal of CO_2 and was supplied to the natural gas grid (Triolo et al., 2013; Vega et al., 2014). The potential production of electricity by the bio-methane yield was assumed to be discounted from the on-farm electricity use. The digestate produced was applied in the fields under baseline conditions but with an increased fertiliser efficiency; substitution rates for N: 85% and P: 100% (Vega et al., 2014).

Table A2.6 contains the emission factors specific to each of the above scenarios. Emissions associated with the storage, treatment, transportation and field application of manure were estimated.

Pig housing alternative scenarios

Nine housing scenarios were developed around variations in the following factors: indoor temperature, ventilation efficiency, level of barn insulation, frequency of slurry removal from barn pits, and level of slurry dilution. Evidence in literature and the outcomes of the sensitivity analysis suggested that these factors have the potential to affect manure composition at pig housing and the system environmental impact.

Indoor temperature

Indoor temperatures for the gestation, lactation, nursery and growing/finishing units were set to their Min and Max reported values (SEGES 2011a; 2011b; 2012; 2017). Modifying indoor temperature directly affects NH_3 emissions and energy consumption for indoor climate regulation at pig housing (Rigolot et al., 2010).

Ventilation efficiency

The main effects of changes in the ventilation efficiency can be observed in the energy consumption for the regulation of indoor climate (Schauberger et al., 2000; Lammers et al., 2010b) and in NH_3 emissions at pig housing (Rigolot et al., 2010). The ventilation efficiency was set to the minimum of fresh air provided at 16.3 m^3 /h W and maximum at 24.5 m^3 /h W (K. Myllerup, personal communication, February 27, 2018).

Barn insulation

Changes in barn insulation have an effect on energy consumption for the indoor climate regulation (heating and ventilation systems) (Schauberger et al., 2000). The U – value of a building describes the sum of all its layers of thermal resistance (insulation). A low U-value = 0.26 W / m^2 K was assumed to represent a very well insulated building and a high U-value = 4 W / m^2 K, to represent a poorly insulated barn.

Slurry removal from barn pits

Increasing the frequency of slurry removal from barn pits has the potential to reduce NH_3 emissions from slurry at pig housing. The study assumed that when slurry removal occurred under baseline conditions, once every 4 weeks or more, no reductions or increases in NH_3 emissions were observed. However, when slurry removal occurred on a daily basis, NH_3 emissions were reduced by 35% (Rigolot et al., 2010). The slurry pumping system was assumed to require 15 kWh of electricity operating at a capacity of 12.5 m^3 slurry / hour.

Slurry dilution

Variations in the level of slurry dilution have a significant effect in the concentration of total ammoniacal nitrogen (TAN) and therefore the emissions of NH_3 from slurry (Génermont & Cellier, 1997; Rigolot et al., 2010). This strategy can potentially be achieved as a side effect of certain farm management activities, such as increasing the water usage during cleaning of the barns and cooling of the animals with sprinklers. For this analysis, the study assumed a 50% dilution caused by the increased water use during cleaning activities and reflected by a 15% decrease in TAN concentration in the slurry (F. Udesen, personal communication, 18 June, 2019). In this scenario, additional fuel required for the transportation of more voluminous, diluted slurry to the fields as well as during the field application process was considered.

The above resulted in 9 pig housing scenarios: 2 indoor temperatures, 2 ventilation efficiencies, 2 levels of barn insulation, 1 frequency of slurry removal and 2 levels of slurry dilution.

2.2.6. Alternative scenario analysis

The alternative scenarios were analysed in a design of 4 manure management (3 alternatives plus the baseline) x 9 pig housing scenarios. Their abatement potential was calculated as the difference in environmental impact when compared to the baseline scenario using 1000 parallel Monte Carlo simulations. With this method, values of standard error ≤ 1% of the mean was reached for most impact categories assessed and high repeatability of results was observed. If an alternative scenario had different (lesser or greater) environmental impact than the baseline for more than 95% of the parallel simulations, then the results were considered significantly different (Leinonen et al., 2012; Mackenzie et al., 2015; Tallentire, Mackenzie & Kyriazakis, 2017).

In addition to evaluating the abatement potential of each alternative scenario, the change in environmental impacts of each manure management system as a response to modifications in pig housing was estimated.

2.3. Results

2.3.1. Sensitivity analysis and environmental impact hotspot identification

Hotspots associated with pig barn characteristics (construction)

Increasing the length of the farrowing barn walls exhibited a relative sensitivity of 3.80% for NREU, while increasing the barn wall height had a relative sensitivity of 2.01% for the same impact category. Increasing the length of the long and short sides of the gestation barn showed a 14.1% and 7.03% relative sensitivity for GWP. All of the above changes resulted to an increased system EI.

Increasing the level of barn insulation was an Environmental Impact Hotspot (EIH) for NREU (5.21%), AP (1.36%), GWP (1.26%) and NRRU (1.18%), helping to reduce the system EI.

Decreasing the lifetime of technologies involved in pig housing was the most sensitive factor for NRRU (relative sensitivity of 63.5%) and an EIH for NREU (2.66%) and GWP (1.07%) increasing the environmental impact for these categories. A decrease in barn lifetime exhibited relative sensitivity of 5.02% for NRRU while it was below 1% for the rest of the impact categories, increasing the system EI in all cases.

Hotspots associated with indoor climate control

Reduced efficiency of the ventilation system showed relative sensitivities of 23.1% for NREU, 8.78% for GWP and 1.21% for the AP, towards an increase of the system EI. Decreasing the indoor temperatures exhibited relative sensitivities across all production stages and helped reduce the system EI as follows: GF unit – AP (5.15%), EP (1.91%), Farrowing unit – NREU (4.40%), AP (1.98%), NRRU (1.66%), GWP (1.15%), Nursery unit – NREU (3.48%), AP (2.85%), EP (1.06%), Gestation unit – NREU (3.44%), GWP (1.30%).

Hotspots associated with slurry handling at pig housing

For an increase in the level of slurry dilution, relative sensitivities of 40.4% for AP, 19.1% for EP, 5.17% for NRRU and 1.81% for NREU were observed, reducing the system EI in all cases. Removing slurry on a daily basis had a relative sensitivity of 10.3% for AP, 3.81% for EP and 1.04% for the NRRU impact categories helping to reduce the system EI. Reductions in the emission factors linked to floor type, slurry storage and field application of manure, and associated with NH_3, PO_4^{3-}, N_2O and NO_3, showed relative sensitivities ≥1% for GWP, AP and EP.

All other parameters included in the sensitivity analysis did not vary the outcome of the LCA significantly and therefore were not identified as potential environmental impact hotspots. Table A2.7 contains the sensitivity analysis results for all the parameters assessed.

Table 2.2: Potential environmental impact hotspots (EIH) associated with pig housing. The table summarises the relative sensitivity for each EIH (%) and across all 5 impact categories. NRRU = Non-Renewable Resource Use, NREU = Non-Renewable Energy Use, AP = Acidification Potential, EP = Eutrophication Potential, GWP = Global Warming Potential, Tech = technological, T = temperature.

Environmental impact category	Barn characteristics (construction)	Indoor climate control	Slurry handling at pig housing
NRRU	Decrease in Tech lifetime – 63.5% Decrease in Barn lifetime – 5.02% Increase in Level of barn insulation – 1.18%	T Farrowing – 1.66%	Level of slurry dilution – 5.17% Slurry removal regime – 1.04%
NREU	Level of barn insulation – 5.21% Tech lifetime – 2.66%	Ventilation efficiency – 23.1% T Farrowing – 4.40% T Nursery – 3.48% T Gestation – 3.44%	Level of slurry dilution – 1.81%
AP	Level of barn insulation – 1.36%	T Growing/Finishing – 5.15% T Nursery – 2.85% T Farrowing – 1.98% Ventilation efficiency – 1.21%	Level of slurry dilution – 40.4% Slurry removal regime – 10.3%
EP		T Growing/Finishing – 1.91% T Nursery – 1.06%	Level of slurry dilution – 19.1% Slurry removal regime – 3.81%
GWP	Level of barn insulation – 1.26% Tech lifetime – 1.07%	Ventilation efficiency – 8.78% T Gestation – 1.30% T Farrowing – 1.15%	

2.3.2. Alternative scenario comparisons

Pairwise comparisons of alternative manure management scenarios

Table 2.4 presents the environmental impact of the different manure management systems under baseline pig housing conditions. Pairwise comparisons between the alternative and baseline manure management scenarios showed that the differences in their environmental performance were significant (different for ≥95% of the simulations) for all EI categories.

Slurry acidification significantly reduced AP (-28.3% difference compared to the baseline) and EP (-14.2%), while it greatly increased NRRU (+45.4%), GWP (8.46%) and NREU (+1.98%). Screw press slurry separation reduced only the NREU category (-2.18%) and increased AP (+62.5%), NRRU (+35.0%), GWP (+6.43%) and EP (+4.67%). Centralised anaerobic digestion exhibited significant reductions in NREU (-40.1%), NRRU (-33.9%) and GWP (-9.29%) categories, while it increased EP (+8.02%) and AP (+6.46%).

Interactions between the pig housing and manure management alternative scenarios

Figures 2.3–2.6 show the percentage change in environmental performance that each alternative configuration caused compared to the baseline, across all Environmental Impact Categories (EICs). Tables A2.8–A2.11 present the environmental performance of all the manure management scenarios under all housing scenarios (baseline and alternative).

Significant interactions between the pig housing and manure management components of the system were identified; all manure treatment alternatives were affected by changes in all housing related factors except for indoor temperature. Although significant, these interactions did not cause any meaningful change in the ranking of manure management alternatives based on their environmental performance. One exception to this was that while slurry separation significantly reduced NREU (-2.18%), it was outperformed by a combination of increased ventilation efficiency and baseline manure management for the same EI category (-2.83%).

Overall, slurry acidification was the most robust manure management scenario to changes at pig housing. Centralised anaerobic digestion was the most sensitive manure management scenario for the NRRU, NREU and GWP impact categories followed by the baseline scenario, which was the most sensitive for AP.

Decreasing insulation significantly increased the environmental impact for NRRU across all manure management scenarios, by a range of 6.64-16.0% compared to the baseline conditions. For

NREU and GWP the ranges of increase were 8.99-15.8% and 2.57-3.24% respectively, across all manure management scenarios. Increasing insulation significantly reduced NRRU by 1.6-4.2% across all manure management systems and NREU by 2.21-3.88%.

The increased ventilation efficiency reduced NREU (1.85-3.08%) and GWP (0.82-1.43%), while lowering the ventilation efficiency increased the environmental impact on the same categories by 1.83-4.61% and 1.22-1.55% respectively.

Increasing the level of slurry dilution resulted to significant reductions of environmental impact for AP (1.95-5.31%), EP (0.39-1.06%) and NREU (0.31-1.51%). Less diluted slurry increased the environmental impact of the system significantly for AP by 1.98-6.74%, EP by 0.26-2.51%, and NREU by 0.35-2.56%. Daily slurry removal reduced AP (0.51-5.45%) and NRRU (0.07-3.26%).

Table 2.4: Environmental impact of the production of 1 kg LW pig at the farm gate. The environmental performance of the alternative manure management scenarios was compared to the baseline, under baseline pig housing conditions. The third row for each impact category presents the significance of difference in percentage of LCA runs. NRRU = Non-Renewable Resource Use, NREU = Non-Renewable Energy Use, AP = Acidification Potential, EP = Eutrophication Potential, GWP = Global Warming Potential.

Impact Category		Baseline scenario	Slurry acidification	Screw press slurry separation	Anaerobic digestion
NRRU (kg Sb eq.)[1]	Mean	3.40 E-07	4.94 E-07	4.59 E-07	2.24 E-07
	St. dev	2.19 E-07	2.28 E-07	1.87 E-07	2.75 E-07
	% of LCA runs ≤ Baseline	NA	1.70	0.00	99.1
NREU (MJ)[2]	Mean	17.7	18.1	17.3	10.6
	St. dev	0.691	0.696	0.671	0.718
	% of LCA runs ≤ Baseline	NA	0.00	100.	0.00
AP (kg SO_2 eq.)[3]	Mean	2.78 E-02	2.00 E-02	4.52 E-02	2.96 E-02
	St. dev	7.60 E-04	3.03 E-04	1.48E E-03	8.23 E-04
	% of LCA runs ≤ Baseline	NA	100.	0.00	0.800
EP (kg PO_4^{---} eq.)[4]	Mean	2.46 E-02	2.11 E-02	2.57 E-02	2.66 E-02
	St. dev	3.97 E-04	2.97 E-04	4.70 E-04	4.53 E-04
	% of LCA runs ≤ Baseline	NA	100.	0.100	0.00
GWP (kg CO_2 eq.)[5]	Mean	3.57	3.87	3.80	3.24
	St. dev	5.10 E-02	5.89 E-02	5.91 E-02	5.81 E-02
	% of LCA runs ≤ Baseline	NA6	0.00	0.00	0.00

[1] Sb = antimony
[2] MJ = Megajouls
[3] SO_2 = sulphate
[4] PO_4^{---} = phosphate
[5] CO_2 = carbon dioxide
[6] NA = not available

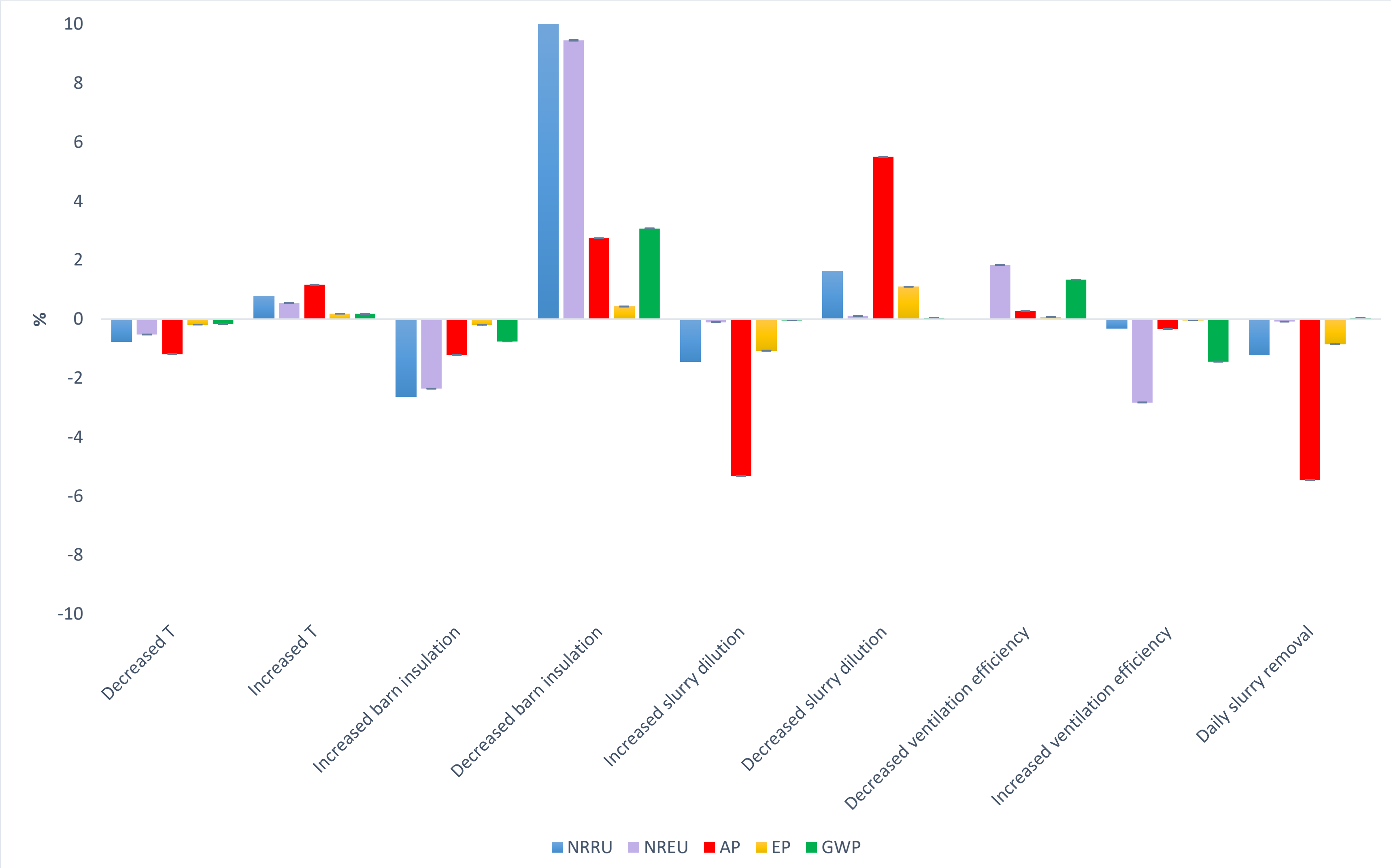


Figure 2.3: Percentage change in environmental impacts of the baseline manure treatment caused by changes in pig housing. NRRU = Non-Renewable Resource Use, NREU = Non-Renewable Energy Use, AP = Acidification Potential, EP = Eutrophication Potential, GWP = Global Warming Potential, T = temperature.

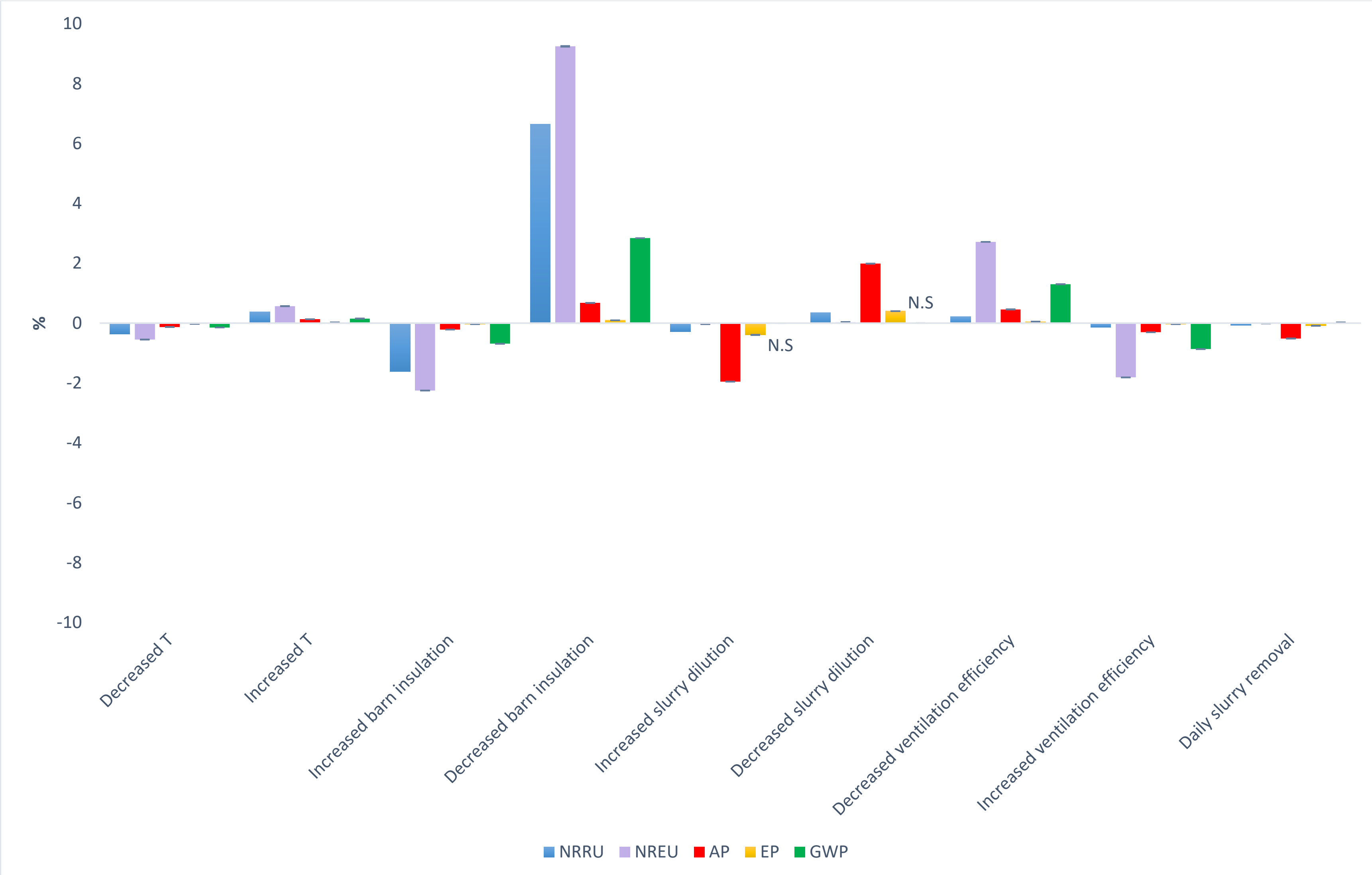


Figure 2.4: Percentage change in environmental impacts of the slurry acidification caused by changes in pig housing. NRRU = Non-Renewable Resource Use, NREU = Non-Renewable Energy Use, AP = Acidification Potential, EP = Eutrophication Potential, GWP = Global Warming Potential, T = temperature, N.S. = non-significant

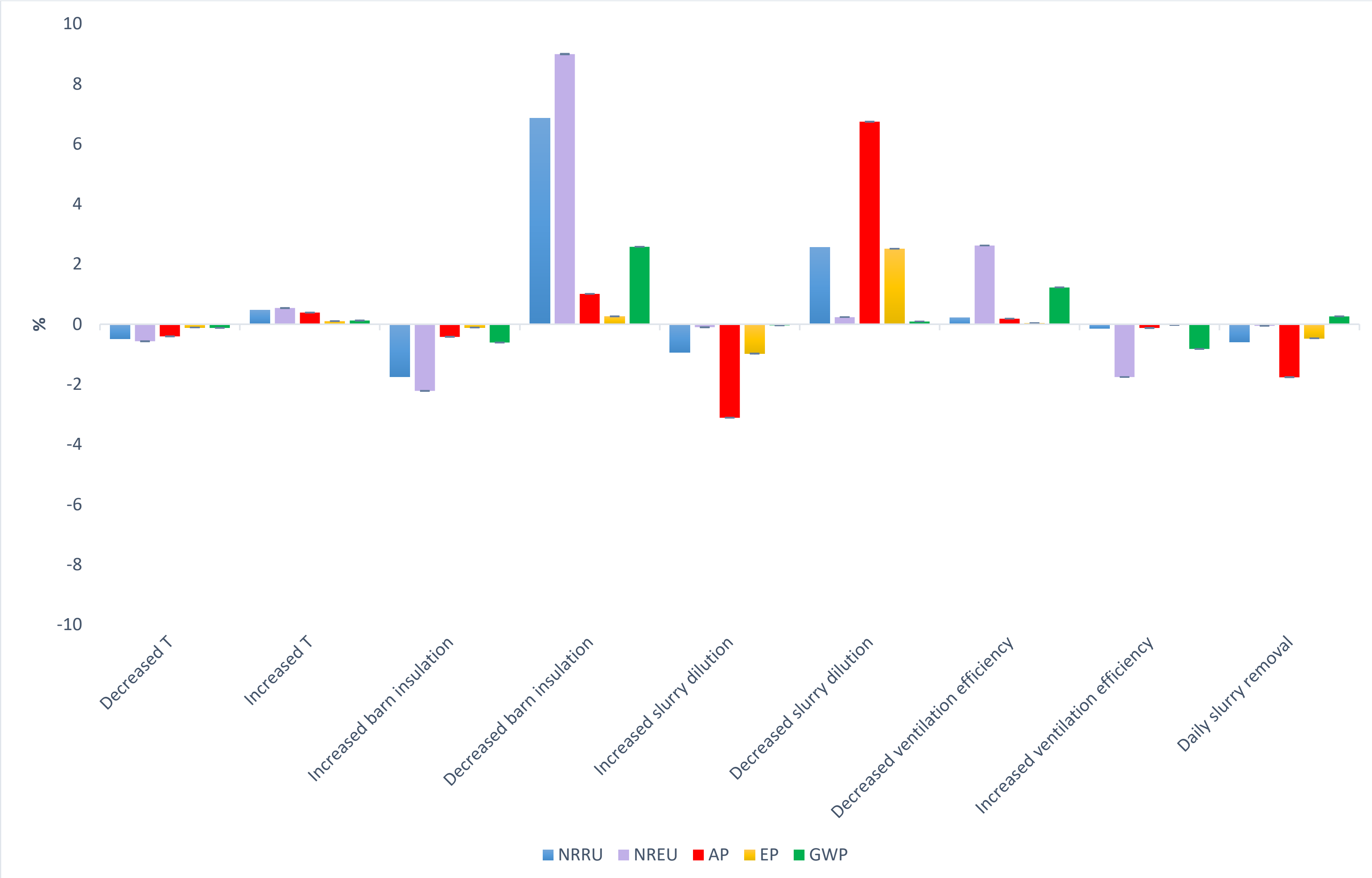


Figure 2.5: Percentage change in environmental impacts of the screw press slurry separation caused by changes in pig housing. NRRU = Non-Renewable Resource Use, NREU = Non-Renewable Energy Use, AP = Acidification Potential, EP = Eutrophication Potential, GWP = Global Warming Potential, T = temperature.

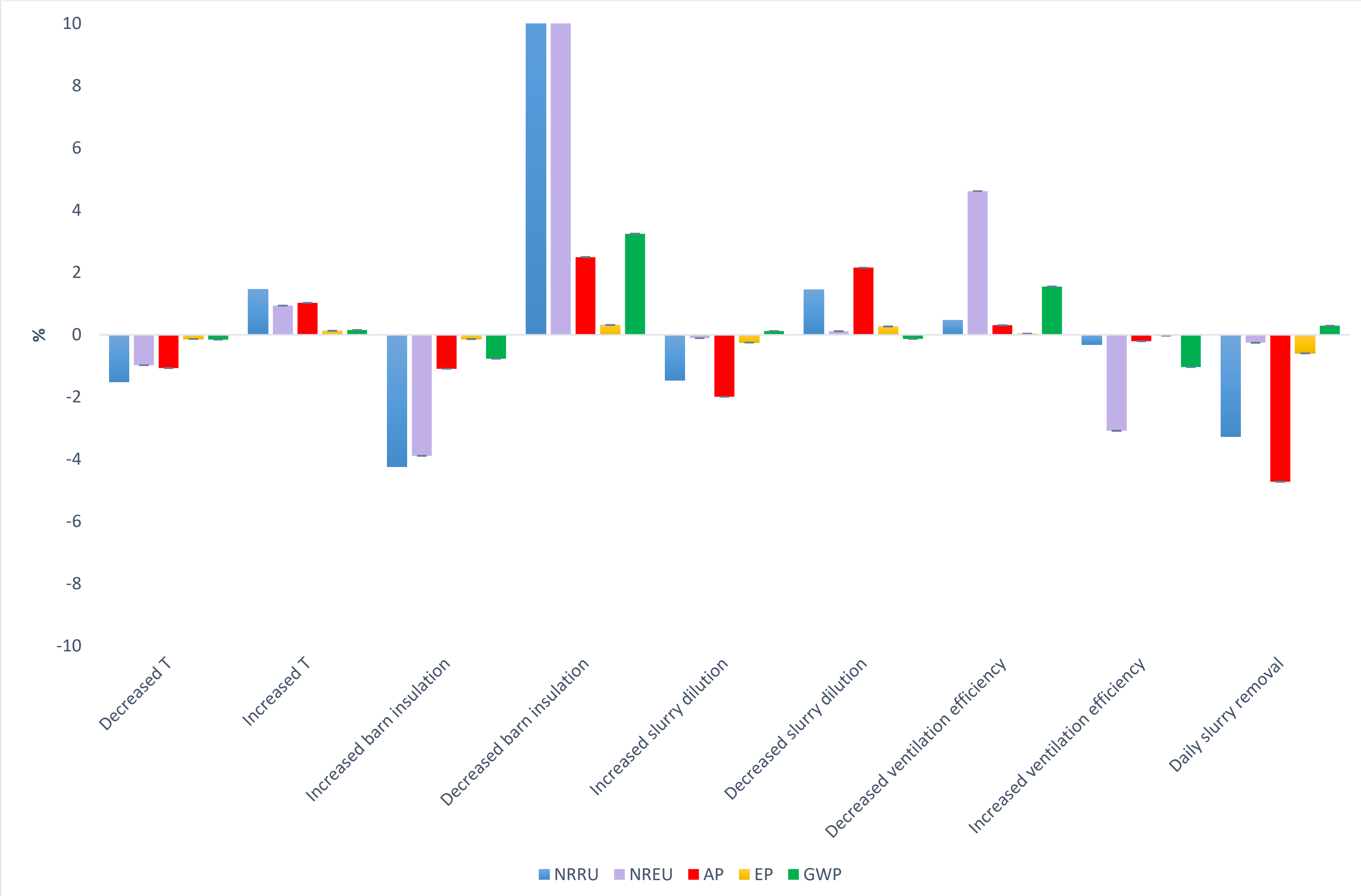


Figure 2.6: Percentage change in environmental impacts of the anaerobic digestion caused by changes in pig housing. NRRU = Non-Renewable Resource Use, NREU = Non-Renewable Energy Use, AP = Acidification Potential, EP = Eutrophication Potential, GWP = Global Warming Potential, T = temperature.

2.4. Discussion

The primary aim of the study was the environmental impact assessment of a European, pig production system from a whole-farm perspective. In addition, it aimed to quantify the environmental consequences of implementing alternative pig housing and manure management strategies using a conventional integrated Danish pig production system as a case in point. The methods presented in this chapter can provide a guideline for the holistic, environmental impact assessment of pig farming systems, accounting for all system components and their interdependencies. By identifying environmental impact hotspots at pig housing and manure management, this study adds knowledge that can potentially facilitate decision making towards the improvement of sustainability in pig production.

Comparing the results of different LCA studies is a difficult task with issues of comparability being associated with the functional unit, system boundaries, scope and assumptions of each study (McAuliffe et al., 2016). Several LCA studies have focused on Danish pig production in the past (Dalgaard, Halberg, Kristensen & Larsen, 2004; Dalgaard, Halberg & Hermansen, 2007; Nguyen et al., 2011), but have not thoroughly considered the housing component, its management and the inclusion of capital equipment. Other studies have investigated the effect of variations in pig housing characteristics on NH3 and CH4 emissions (Hutchings, Sommer, Andersen & Asman, 2001; Møller et al., 2004; Rigolot et al., 2010). Some have also compared the environmental performance of various manure management technologies (Amon et al., 2007; Wesnæs et al., 2009; Chadwick et al., 2011; Cherubini et al., 2015).

In this study, all components of the pig farming system and their interdependencies were considered. As expected the feeding component (including feed production and delivery of feed and water to animals) was overall the largest contributor to the system environmental impact. Nonetheless, the sizeable contribution of the pig housing and manure management components to the system environmental impact suggests that they should not be disregarded in LCA studies of pig production systems. The study showed that the pig housing (construction and management) contributed ~65% to NRRU, ~52% to NREU and ~35% to GWP. Energy consumption for the indoor climate regulation (heating and ventilation systems) explained most of the pig housing component's contribution to GWP and NREU, while the NRRU impact was attributed to the use of the various construction materials. The largest contribution of the manure management component (including emissions from slurry storage and field application levels) was ~20% to the

AP and EP impact categories. Emissions related to pig growth and slurry handling at the pig housing level also showed a contribution of ~24% to AP and EP. Thus, although lower than the feeding component, the contribution of the pig housing and manure management components to the system environmental impact is not negligible.

Some limitations of this study were acknowledged. Animal performance related factors were assumed fixed when examining the sensitivity of the model. The public availability of further data on the interactions between animal performance and pig housing related parameters, would allow for a more complete evaluation of the pig system and its environmental performance. Variations in the feeding strategy and diet formulations can have an effect on the abatement potential of the alternative manure management scenarios investigated in this study. For example, the use of low – crude protein diets, dry or liquid feeding systems can potentially affect the observed abatement potential of such mitigation strategies when compared to baseline conditions (Garcia-Launay et al., 2014; Mackenzie et al., 2016). Adding alternative feeding scenarios would allow for an even more comprehensive exploration of the synergies between mitigation strategies in the various components of the pig farming system and is a potential area for future development of the framework.

Due to data limitations regarding the specific degradation rates for each compartment of the housing system, lifetimes were considered to be the same and vary in the same manner for the different parts of the barn (50 years average) and the various technologies involved (20 years average). Having access to additional information relative to the dimensions, properties and lifetimes of the different insulation materials used in barn construction, would enhance the model's applicability and precision.

Notwithstanding the difficulties in adopting whole-farm, life cycle modelling approaches this study presents an elaborate framework that can be effectively used to evaluate the abatement potential of modifications in any component of the pig production system

2.4.1. Abatement potential of modifications in pig housing

Barn characteristics and indoor climate control

The technological lifetime was identified as a hotspot for NRRU, NREU and GWP, while the barn lifetime was identified as a hotspot for NRRU as confirmed by previous studies (Lammers et al., 2010a, Häfliger et al., 2017). The results suggest that developing enduring construction materials and improving the efficiency of technological developments, can significantly help reduce the system environmental impact for the above categories. The trade-offs between the longevity of pig housing and obsolescence should be considered, especially for the case of technological equipment (e.g. climate control, feed distribution, etc.), as technological innovations continue to enhance the energy and environmental efficiency of modern pig housing systems. Identifying the optimal frequencies of renewal in the context of technical progress in building and material design is a potential area for further research.

The choice of construction materials, level of insulation and type of insulation material used have a significant effect on the environmental impacts of residential and commercial buildings (Shrestha, Bhandari, Biswas & Desjarlais, 2014; Häfliger et al., 2017). A few studies have considered the impact of such choices for pig houses (Lammers et al., 2010a). The results of this study confirm the evidence in literature. The level of barn insulation was identified as a factor with potential to significantly affect NRRU and NREU across all manure management systems tested, mainly due to its correlation to energy consumption at the pig housing level. Increasing the amount of construction materials used for the pig housing system, as reflected by changes in the barn and pen dimensions, affected the GWP category. More effort should be directed towards quantifying the implications of alternative barn designs and construction material on the environmental impact of livestock production systems.

Slurry handling at pig housing

Increasing the level of slurry dilution significantly reduced the AP and EP categories, which is explained by a decrease in total ammoniacal nitrogen concentration resulting in reduced ammonia emissions. This strategy could potentially be achieved as a side effect of water-based cooling systems in pig housing (Jeppsson, Olsson & Häggström, 2018). While significant effects were not observed on the system EI due to increased fuel usage for the transportation of the more voluminous diluted slurry, the importance of identifying the critical point beyond which the reductions in AP and EP are outweighed by increases in other EI categories is acknowledged. For a more sophisticated scenario, the effect of slurry dilution on the efficiency of slurry pumping systems and technologies involved in manure management should also be considered.

Increasing the rate of slurry removal from the barn-pits significantly reduced the environmental impact for the AP and EP categories, as was also reported in previous studies (Rigolot et al., 2010;

Philippe et al., 2011). The additional energy required for the operation of the slurry pumping system was included in this study, but removing slurry from the barn on a daily basis would also require extra working hours (manual labour), and / or the use of additional technological equipment. The environmental and economic consequences of such environmental impact mitigation strategies should be carefully considered prior to their implementation and when evaluating their effectiveness.

Overview of potential environmental impact hotspots at pig housing

Overall, the biggest changes in environmental impacts, for all manure management systems, were observed due to variations in the level of barn insulation, slurry dilution and the frequency of slurry removal. The most sensitive EI categories were NRRU, NREU and AP. Such an outcome was anticipated, since most of the input parameters in the model have either direct or indirect effects on energy consumption (e.g. ventilation efficiency, barn insulation) and nitrogen – related emissions (e.g. ammonia).

Past studies have suggested that when targeting to reduce GWP and NRRU, modifications in the feed production and diet formulation are a very efficient strategy to follow (Nguyen et al., 2011; Mackenzie et al., 2016). This study proposes that significant reductions can also be achieved when considering alternative barn designs with more sustainable construction materials and improving slurry handling practices at pig housing (e.g. daily slurry removal).

2.4.2. Abatement potential of alternative manure management strategies

Slurry acidification was the best performing manure management option for AP and EP. In this study, the addition of calcium carbonate during field application to counteract the acidic effect in the soil was considered; the reaction produces calcium sulphate, water and CO2 which is captured by photosynthesis (short-cycled carbon) (Saue & Tamm, 2018). However, volatile sulphur-containing compounds can be formed in many stages of the process and have adverse effects not only on the environment but also on the animals (Borst, 2001). Acidification can obstruct the solution of metal complexes, which can be released in ground water potentially increasing eco-toxicity and human toxicity risks (Saue & Tamm, 2018). Access to data that describe such processes was a limiting factor in this study and an area for further improvement.

Anaerobic digestion of slurry resulted in great reductions for GWP and NREU mainly. This manure management method consists of very complex processes. The number of farms feeding the centralised plant, the properties of substrate for co-digestion, the end – product from biogas (electricity, heat) and where this energy is supplied, are examples of parameters that need to be explored in detail in order for the model to be able to fully capture the impacts of this system. Particularly, with the recently signed energy agreements that call for a "55% renewable energy target" until 2030 (Danish Energy Agency, 2018) and expansion of the production of green biogas, it is important that more holistic studies are conducted to thoroughly investigate the environmental impacts of this strategy.

Through the implementation of slurry separation, a significant reduction in NREU was identified. The study acknowledges the potential for reductions in AP and EP through nutrient re-distribution; public availability of relevant data would enhance the model accuracy when modelling such alternatives. The newer limitations imposed by legislation (30kg phosphorus per hectare, from 2025) (Ministry of Environment and Food of Denmark, 2017), call for estimators that describe in detail various scenarios of the storage, transportation and field application of the solid fraction in particular, and are able to assess the performance of the screw press separation system for various site specific conditions.

2.4.3. Interactions between pig housing and manure management

The scenario analysis results revealed significant interactions between the pig housing and manure management components of the system. This outcome was anticipated, due to the outcomes of the sensitivity analysis, which suggested the importance of several housing related factors as potential environmental impact hotspots.

Slurry acidification exhibited the least sensitivity against modifications in pig housing. Adding sulphuric acid in slurry greatly reduces ammonia emissions and so variations in factors that affect NH3 emissions at pig housing (e.g. slurry dilution), would have a less noticeable effect on acidified than on untreated slurry. Large reductions in AP and EP can be observed with this manure management method regardless of the pig housing conditions. Implementing it under baseline housing conditions should be preferred to avoid potential additional costs to achieve only small improvements in environmental performance. Slurry acidification is mainly applied in Denmark and for the larger pig farming systems (Ten Hoeve et al., 2016). However, its robust performance suggests that it could potentially be used in a variety of systems across Europe.

Anaerobic digestion was also quite robust for NRRU, NREU and GWP, where it achieved the largest reductions among all alternatives. Modifications at pig housing would not noticeably impact these EI categories when combined with anaerobic digestion , unless they significantly affected the manure properties that are directly related to its biogas production potential (e.g. dry matter content, density). Variations in the level of slurry dilution could have this effect and propose that such interactions should be thoroughly investigated whenever data is available.

Slurry separation exhibited similar sensitivity with AD to modifications at pig housing. With this manure management method, a greater effect could be observed in EI if manure physical properties would change, e.g. due to dilution of slurry, rather than its chemical composition, e.g. through the reduction of NH_3 emissions. Accounting for all potential effects on the separation efficiency of this technology is important to fully understand its abatement potential.

2.5. Conclusions

A life cycle assessment approach is the only way that the effect of interactions between the different components of a pig production system on its environmental impact can be quantified. It is important in the assessment of the potential environmental impact of pig farming systems to consider equally all their components: feed production, animal production, pig housing and manure management. This study suggests that the latter can contribute significantly to certain EI categories. Modifications in manure management were shown to be effective when aiming to reduce the environmental impact of the pig farming system. However, the environmental performance of the manure management alternatives was sensitive to factors related to pig housing, the most important of which were the level of barn insulation, level of slurry dilution, the rate of slurry removal from the barn and the efficiency of the ventilating system. Therefore, interactions between the pig housing and manure management components should be considered when targeting the improved environmental performance of the pig farming system.

Chapter 3. Cost-effectiveness of environmental impact abatement measures in a European pig production system

Abstract

Many emerging technologies and alternative farm management practices have the potential to improve the sustainability of pig production systems. However, the implementation of such practices is not always economically viable. The goal of this study was to assess the cost-effectiveness of such environmental mitigation strategies in pig systems, using an Environmental Abatement Cost (EAC) analysis.

Four pig housing (improved insulation–IMIN, increased ventilation efficiency–IVE, frequent slurry removal–FSR, increased slurry dilution–ISD) and three manure management related abatement strategies (anaerobic digestion–AD, slurry acidification–Acid, slurry separation–SP) were considered, implemented as stand-alone measures and as a set of "pig housing–pig housing" and "pig housing–manure management" combinations. The baseline system against which the analysis was conducted was a typical Danish pig production system, over a 25-year time horizon. The environmental impact categories considered were Non-Renewable Resource Use (NRRU), Non-Renewable Energy Use (NREU), Global Warming Potential (GWP), Acidification Potential (AP) and Eutrophication Potential (EP). First, a Discounted Cash Flow analysis was conducted, where the whole-farm Annual Equivalent Value (AEV) was estimated for each stand-alone investment and all possible combinations of their implementation. The top-10 combinations based on their AEV were selected. Then, the annualised abatement potential of each abatement scenario-investment was calculated using a cradle-to-farm-gate life cycle assessment model. The selected abatement measures (stand-alone and top-10 combinations) were tested and their cost-effectiveness was compared for each impact category through the EAC.

Pig housing–AD combinations were the most cost-effective options for GWP, NRRU and NREU. Their abatement costs ranged from -€0.237 to €0.70 per tonne CO_2 eq., -€0.146 to €0.36 per g Sb eq. and -€1.75^{-04} to €3.11^{-04} per GJ abated respectively. AD was the most cost-effective stand-alone investment for GWP (-€0.206 per tonne CO_2 eq.), NRRU (-€0.0493 per g Sb eq.) and NREU (-€1.00^{-04} per GJ), and Acid the most cost-effective for AP (€303 per tonne SO_2^- eq.) and EP (€1,190 per tonne PO_4^{3-} eq.) mitigation. Of the "pig housing – pig housing" combinations, IMIN & IVE, IVE & FSR and IVE & ISD were identified as cost-effective options for the mitigation of the impact categories considered. Overall, measures for mitigation of GWP, NRRU

and NREU required higher investments than for AP and EP, but also exhibited negative abatement costs (profits).

The framework developed in this study can potentially aid decision making in the choice of environmentally and economically sustainable pig system modifications.

3.1. Introduction

A key sustainability target of the 21st century is to evaluate and reduce the environmental impacts (EI) associated with livestock production, while addressing the increased demand for meat products (European Commission, 2019). Pig production constitutes the largest sector in the meat industry globally and accounts for 18% of the greenhouse gas emissions associated with livestock production, also contributing to freshwater eutrophication and the acidification of ecosystems (Lopez-Ridaura et al., 2009; Dennehy et al., 2017). Considering the increasing popularity of pork meat, the emissions arising from pig production systems cannot be neglected (Opio et al., 2013).

Past studies have identified the feed production component as the largest contributor to environmental impacts arising from pig farming systems (Basset-Mens & Van der Werf, 2005; Nguyen et al., 2011). Consequently, much effort has been put into the adaptation of feeding methods and development of alternative diet formulations targeting less pollution (Reis, Howard & Sutton, 2015; Mackenzie et al., 2016; Pierer et al., 2016). Other studies have highlighted the potential for EI reductions by implementing alternative manure management components of the pig farming system (Groenestein, Smits, Huijsmans & Oenema, 2011), such as slurry acidification (Acid) or anaerobic digestion (AD) for the production of electricity and heat (Ten Hoeve et al., 2014; Cherubini et al., 2015). Physical characteristics (e.g. level of barn insulation) and management (e.g. climate control, slurry handling at pig barn) of the pig housing component, have been identified as important factors that can significantly affect system environmental impacts (Rigolot et al., 2010; Philippe & Nicks, 2015; Santonja et al., 2017). Modifications in pig housing and manure management have the potential to reduce on-farm energy use (-40%), the potential for acidification of ecosystems (-28%) and global warming potential (-9.24%) (Pexas, Mackenzie, Wallace & Kyriazakis, 2020a).

Alongside the significant abatement potential of alternative management strategies, realising their implementation in an economically viable manner is pivotal in farmer decisions (Sefeedpari et al., 2019). Decision making regarding investments that target the improved sustainability of a pig farming system require the assessment of many factors both environmental (e.g. abatement potential) and economic (e.g. cost of investment, maintenance, productivity). Accordingly, comprehensive assessment of the cost-effectiveness of alternative investments often requires sophisticated analysis of any benefits and costs associated with their implementation (Montalvo, 2008; Reis et al., 2015; Miah, Koh & Stone, 2017). Bio-economic analysis may be used to combine environmental and economic models to simulate the complex linkages between these two aspects of farming systems (Kragt, 2012). From an environmental perspective, life cycle assessment (LCA) models are used widely to evaluate the EI associated with the operation of a supply chain and to compare the environmental performance of alternative system configurations (Guinée, 2002; Van der Werf & Petit, 2002). From an economic perspective, valuation methods such as discounted cash flow, real options and cost – benefit analysis are routinely used for the economic appraisal of long-term investment projects (Dixit & Pindyck, 1994; Nolan et al., 2012; Yazan et al., 2018). In the case of pig farming, the literature comprises relatively few models that simulate the entire system taking into account novel management strategies for their improved sustainability. The focus for the majority of these models has been the relative contribution and abatement potential of modifications in the feeding and breeding components of the pig farming system (Lopez-Ridaura et al., 2009; Garcia-Launay et al., 2014; Ali, Berentsen, Bastiaansen & Lansink, 2018). Therefore, there is a need to develop approaches that evaluate pig production systems through a whole-farm perspective and consider all system components along with their interactions (Huijbregts et al., 2001; Prapaspongsa et al., 2010a; Lammers, 2011).

Evaluating the cost-effectiveness of proposed abatement measures could provide a practical and easy to interpret indicator that would combine the individual environmental and economic performance scores. Cost-effectiveness is a function of the cost of implementation and abatement potential associated with a particular mitigation strategy. Environmental abatement cost (EAC) curves have been used as a tool to graphically present and compare the cost-effectiveness of any set of such modifications and facilitate decision making in achieving the improved sustainability of a farming system (Moran et al., 2010; Eory et al., 2013; Stokes et al., 2014; Tomaschek, 2015).

The goal of this study was to develop an integrated modelling framework to evaluate the environmental and economic consequences of a pig farming system. The framework was applied to evaluate the cost-effectiveness of a set of environmental abatement measures related to the pig housing and manure management components of a conventional, Danish pig production system, for five different potential environmental impacts. The presented framework aims to facilitate decision-making regarding cost-effective pig farm investments that target reductions in specific environmental impacts.

3.2. Materials and Methods

To achieve the goal of this study, a bottom-up, technology based environmental abatement cost method was followed. The assessment was carried out through the following steps:

i) The baseline system was described, and 4 pig housing and 3 manure management related abatement measures were identified based on literature. The abatement measures were considered both as stand-alone scenarios and implemented as combinations of "pig housing–pig housing" and "pig housing–manure management" related measures.

ii) An economic model was developed to simulate any cost and revenue streams associated with the pig farming system. Through this model, a discounted cash flow analysis was performed and the annual equivalent value (AEV), net present value and internal rate of return were estimated for the baseline pig farm over a 25-year period.

iii) The above analysis was performed for the pig farm assuming the implementation of each stand-alone abatement measure and any potential combination. This step was used as a screening process to select the top-10 combinations of abatement measures based on the whole-farm AEV they exhibited.

iv) A cradle-to-gate LCA was developed to estimate the environmental performance of the pig farming system and all abatement measures considered (stand-alone and top-10 combinations), for five different EI categories.

v) The economic and environmental outputs were used to estimate the cost-effectiveness of the abatement measures (stand-alone and top-10 combinations) for each EI category separately.

Figure 3.1 below presents a flowchart of the methodological steps followed.

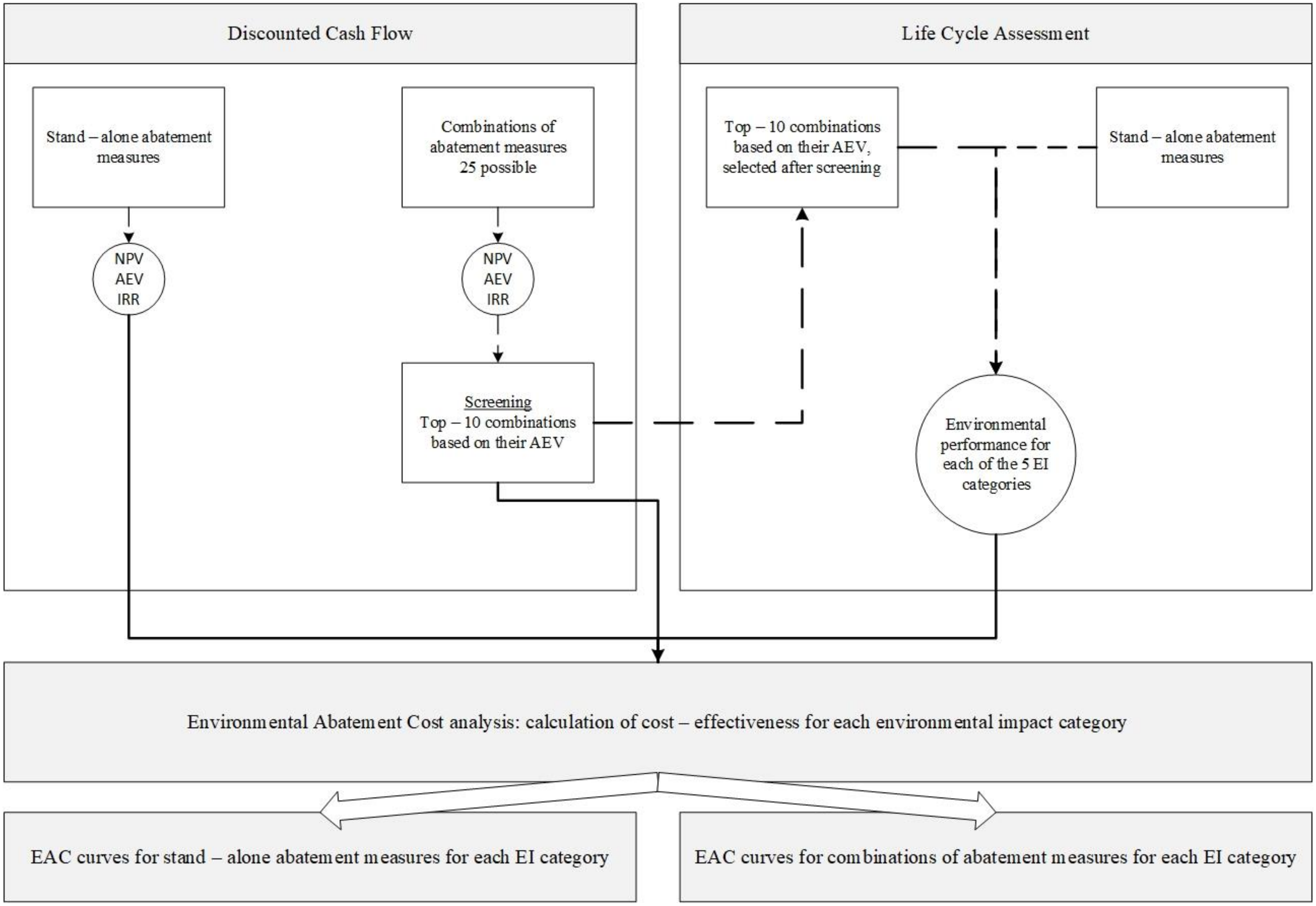


Figure 3.1: Flowchart of the methodological steps followed in this study. Economic and environmental performances were estimated in parallel for the different scenarios (baseline and abatement scenarios). Cost-effectiveness was then calculated to provide context for the construction of environmental abatement cost curves. NPV = Net Present Value, AEV = Annual Equivalent Value, IRR = Internal Rate of Return, EI = Environmental Impact, EAC = Environmental Abatement Cost

3.2.1. Pig farming system description and data sources

Denmark was selected as the study area based on good data quality and the relative homogeneity in pig production systems exhibited across the country. Analyses were performed on a 500-sow, integrated pig production system that produced slaughter pigs at 110kg in Denmark, defined as the representative integrated Danish pig farm (SEGES, 2011a, 2011b, 2012, 2017; Udesen, 2018). The system followed a three-week batch farrowing system. The animals were offspring of Danish Landrace x Yorkshire sows with Duroc sires. A detailed description of animal performance and breeding characteristics from cradle-to-farm gate can be found in Tables A3.1-A3.5 of the Appendix. In addition to this baseline model, scenarios were developed to simulate modifications in the pig housing and manure management components that aim to mitigate the system environmental impact (Section 3.2.3). These scenarios were selected and developed based on literature (Rigolot et al., 2010; Ten Hoeve et al., 2014; Santonja et al., 2017).

3.2.2. Business as usual scenario

Under baseline conditions (Business As Usual scenario – BAU), pig housing was defined by insulated barns (fiberglass-wool batts), partially slatted floors (67% slatted: 33% solid), under-barn slurry pits and a low-pressure ventilation system complying with the Best Available Techniques guidelines for rearing of pigs (Santonja et al., 2017). Slurry handling at pig housing included the flushing of slurry from the slurry pits at intervals of more than 4 weeks. Cleaning activities occurred once at the end of the different production stages (gestation, lactation, nursery and growing/finishing). Feed production and herd performance characteristics were assumed to be unaffected by modifications in pig housing and manure management (Pexas et al., 2020a). In the BAU scenario, manure management was defined by the storage of liquid slurry in outside, concrete, covered slurry tanks and its application in the fields as untreated, organic fertiliser in close proximity to the farm (average distance of 8km). Nutrient substitution rates (avoided use of synthetic fertiliser) were assumed to be 75% for nitrogen, 97% for phosphorus and 100% for potassium (Nguyen et al., 2011; Ten Hoeve et al., 2014). Table 3.1 contains a list of the main economic variables that describe pig housing and manure management under baseline conditions. The Appendix contains a detailed description of the feed production, animal growth, pig housing and manure management components of the pig production system simulated in this study.

Table 3.1: Main costs associated with the pig housing and manure management components of a typical integrated Danish pig farm (500-sow herd) that produces slaughter pigs at 110kg. Revenue streams arising from the production of pig meat (slaughter pigs and culled sows) and field application of pig manure as fertiliser under baseline conditions are also presented.

Variables	***Unit***	***Costs/Revenues***	***Sources***
Energy related costs			
Diesel fuel	€ per litre	1.35	StatBank Denmark
Electricity from the national grid-household price	€ per kWh	0.100	>>
Electricity from the national grid-household price	€ per kWh	0.0949	>>
Electricity from natural gas	€ per kWh	0.0912	>>
Pig housing & manure management related costs			
Concrete, 35 Megapascal (MPa)	€ per m^3	123.	Udesen (2018)
Fiberglass-wool batts	€ per m^2	11.3	>>
Plastic (PVC) used for penning	€ per m^2	34	>>
Labour, wage	€ per working hour	22.5	FADN
Water (incl. drinking water and cleaning water)	€ per litre	0.00840	StatBank Denmark
Annual maintenance costs for building and technological equipment (gestation / lactation)	€ per sow	27.8	Udesen (2018)
Annual maintenance costs for building and technological equipment (nursery)	€ per weaner	3.30	>>
Annual maintenance costs for building and technological equipment (growing/finishing)	€ per grower / finisher	6.00	>>

Annual maintenance costs for manure application machinery	% of initial cost	13.0	>>
Discount rate, long term investment	% of total cost of investment	2.83	StatBank Denmark
Cost of installation (incl. labour, machinery, consumables)	% of total cost of investment	20.0	Udesen (2018)
Annual maintenance of buildings and technological equipment	% of total cost of investment	2.50	>>
Insurance (buildings, technological equipment)	% of total cost of investment	0.250	>>
Revenues			
Slaughter pig	€ per kg live weight	1.15	Hansen (2018)
Culled sow	€ per kg live weight	0.630	>>
Urea fertiliser	€ per kg	0.314	Adapted from FAO (2015)
Di ammonium phosphate fertiliser	€ per kg	0.460	>>
Potassium chloride fertiliser	€ per kg	0.339	>>

3.2.3. Abatement measures

Pig housing abatement measures

Four pig housing related abatement measures that included modifications in slurry handling at pig housing (frequent slurry removal and increased slurry dilution), barn construction (improved insulation) and indoor management (increased ventilation efficiency) were constructed (Santonja et al., 2017).

Frequent slurry removal (FSR)

For this measure, slurry removal activities from the pens and barn pits of the pig housing component were intensified. Flushing of the slurry took place on a weekly basis, as opposed to increments of more than 4 weeks (BAU scenario). There is evidence in literature that this strategy can significantly reduce NH_3 emissions at pig housing (Rigolot et al., 2010). Trade-offs in potential NH_3 emission reductions that could be achieved with this abatement measure, include an increase in manual labour required for the operation of the pig production system, from 0.01 to 0.08 hours per pig per year (Udesen, 2018).

Increased slurry dilution (ISD)

This can be achieved by the addition of water directly at the storage facilities or potentially as a side effect of other farm management strategies, such as increased cleaning of the barns and cooling of the animals with sprinklers. The study assumed that slurry dilution caused by 50% increased water use during cleaning activities, resulted to a 20% decrease in NH_3 concentration in the slurry (total ammoniacal nitrogen) (Aarnink & Elzing, 1998; Santonja et al., 2017). While this abatement measure has the potential to reduce NH_3 emissions at pig housing, it requires an increase in water consumption and the increased slurry volume incurs additional transportation costs associated with its application in the field.

Improved insulation (IMIN)

Increasing the level of insulation in the pig barn has been identified as a strategy that can potentially reduce the system environmental impact for NREU and GWP, among other impact categories (Pexas et al., 2020a). Here, the use of the commercially available insulation material "Polyurethane insulation boards – PUR" was considered, which is two times more efficient in thermal insulation than fiberglass, with thermal transmittance values of $U_{PUR} = 0.16$ W / m² K and $U_{Fiberglass} = 0.33$ W / m² K. The PUR material is however 0.4 times more expensive than fiberglass (Jelle, 2011).

Increased ventilation efficiency (IVE)

For high run-time systems such as in the case of this study (>500 hours annually), maintenance is a dominant factor affecting the system performance. Poor maintenance of the ventilation system and surrounding pig housing components can lead to uneven air flows in the building and reduce fan efficiency by 50% or more (Harner III, Murphy, Brouk & Smith, 2000). For this scenario, a 20% increase in fan efficiency was simulated as an abatement measure, caused by a 50% increase in annual maintenance (including the replacement of damaged parts) (DOE, 2003; AHDB, 2016).

Manure management abatement measures

Three manure management alternatives were considered. These represent the most commonly used manure management strategies in Denmark, with potential to reduce system environmental impact (Ten Hoeve et al., 2014; Pexas et al., 2020a).

Slurry acidification (Acid)

In-house acidification of the slurry has the potential to significantly reduce the AP and EP impact categories by reducing NH_3 emissions at the pig housing storage, outside storage and field application stages of manure management. Acidification was considered as an automated process that did not require an additional input in manual labour. It was assumed that the farmer needed to invest in an acidification plant and pumping system (Kai et al., 2008; Santonja et al., 2017). The operating expenses for this scenario included the purchase and addition of 9.7 kg highly concentrated sulphuric acid (96% H_2SO_4) and 15 kg of calcium carbonate ($CaCO_3$) per tonne of slurry acidified, as well as the additional 3 kWh per m^3 of slurry acidified of energy required for the process (Pedersen, 2004; Ten Hoeve et al., 2014). The acidified slurry was stored and applied under the same conditions as in the BAU (Kai et al., 2008; Fangueiro et al., 2015; Pexas et al., 2020a). The additional cost associated with the implementation of in-house slurry acidification are presented in Table 3.2.

Anaerobic digestion (AD)

In Denmark, AD is a rapidly expanding waste treatment strategy and there is an expected increase for both on-farm and centralised AD of livestock waste over the next years (Al Seadi, 2017). Due to limited data availability, a simplified on-farm anaerobic digestion scenario was developed instead of the more complex centralised AD case. The co-digestion of pig slurry with grass silage was simulated on-farm, for the production of electricity and heat from biogas at a combined heat and power plant (CHP) operating at an 80% efficiency. The energy produced was assumed to be discounted from on-farm electricity use. In addition, the process produced a digestate that was applied under baseline conditions (no further treatment) to replace the use of synthetic fertiliser in crop production. The initial capital investment of this scenario included an additional investment for the AD plant, the CHP plant and the connection to the national electricity grid. The operating expenses included maintenance of the facilities, purchase of the co-substrate and the labour input. This scenario was developed by adapting economic data reported by Nolan et al. (2012) to the case study; i.e. hourly wages and co-substrate prices were translated to Danish standards. The study assumed that digestate was directly applied on field without further treatment (Table 3.2).

Slurry separation (SP)

Slurry separation produces two fractions (solid and liquid) of different nutrient compositions. In addition, it can help reduce transportation costs for field application of slurry (Groenestein et al., 2011; Ten Hoeve et al., 2014). For this scenario, slurry separation by screw press was modelled as it is one of the most commonly used systems in Denmark. The process was assumed to take place at manure storage. The liquid fraction was applied in close proximity to the farm (~8km) under baseline conditions. The fibrous, phosphorous rich and less voluminous solid fraction was transported and applied ~100km from the farm, using broadcast spreading and rapid incorporation.

Table 3.2 contains additional costs associated with the implementation of slurry separation by screw press.

Table 3.2: Costs associated with the implementation of the pig housing and manure management related abatement measures, on a typidal integrated Danish pig farm. Costs associated with the field application of slurry are also included. AD = on-farm anaerobic digestion

Variable	Unit	Cost	Sources
Additional labour for more frequent slurry removal	€ per sow per year	1.58	Udesen (2018)

Additional water used for cleaning activities – increased slurry dilution	% of baseline	50.0	Udesen (2018); Santonja et al., (2017)
Additional maintenance for improved ventilation efficiency	% of baseline	50.0	DOE (2003)
Polyurethane insulation boards (incl. installation)	€ per m^2	16.7	Jelle (2011)
Acidification plant (incl. pumping system)	€ per unit	16,495	SEGES (2015); Santonja et al., (2017)
Sulphuric acid 96% (H_2SO_4) per kg	€ per kg	0.0673	>>
Calcium carbonate ($CaCO_3$)	€ per kg	0.102	>>
Total on-farm AD project costs (incl. connection to grid & other fees)	€ per unit	556,833	Adapted from Nolan et al., (2012); Santonja et al., (2017)
Total on-farm AD operating expenses (incl. labour, co-substrate, maintenance)	€ per m^3 manure treated	14.2	>>
Screw press separator (incl. mixer, separator, controls, pumping system)	€ per unit	36,913	Santonja et al., (2017)
Manure application with broadband spreading and rapid incorporation	€ per m^3 manure	2.00	Udesen (2018)

3.2.4. Economic model

A bottom-up, process-based method was followed for the calculation of the relevant costs and revenue streams. First, a comprehensive list of data was assembled from literature and publicly available sources (SEGES, FADN, Statistics – Statbank Denmark) to describe the life cycle costs associated with each abatement scenario. Data were collected over the 2012 – 2017 period and the average values were used, whenever this was possible. Output and input prices were normalised using mean values over 2012 – 2017 to smooth inter-year variability. Budgeted cash margins per kg of live weight pig meat were assumed constant in real terms over the investment planning horizon (25 years). A description of the specific assumptions considered for the development of the economic model can be found in the Appendix. This modelling approach is consistent with the Life Cycle Cost Analysis method, but due to data constraints economic flows associated with the end-of-life disposal of the capital equipment were not captured (i.e. we assumed 0% salvage value).

The net present value (NPV), annual equivalent value (AEV) and internal rate of return (IRR) were estimated through a discounted cash flow analysis over the 25-year time horizon for the pig farm under baseline conditions and for the implementation of every abatement measure considered (Eq. 3.1-3.2).

$$(\mathbf{Eq. 3.1}) \quad NPV = \sum_{t=1}^{T} \frac{REV_t - OPEX_t - RenC_t}{(1 + DR)^t} - ICI$$

$$(\mathbf{Eq. 3.2}) \quad AEV = \frac{DR(NPV)}{1 - (1 + DR)^T}$$

Where: T = total number of years in the time horizon (25 years), t = each year, REV = revenues, $OPEX$ = operating expenses, $RenC$ = periodic renewal costs for technological equipment where their economic life was less than 25 years, ICI = initial capital investment, DR = discount rate.

AEV is a measure of the annualised monetary return for an investment. It is a metric commonly used to compare the performance of alternative investments, where higher annual equivalent values are generally preferred. This metric was used to guide the selection of the top ten combinations of abatement measures, based on their economic performance. Tables A3.2 and A3.3 of the Appendix, provide a breakdown of costs associated with the production of 1 kg of live weight slaughter pig under baseline conditions and with the implementation of each of the selected abatement scenarios.

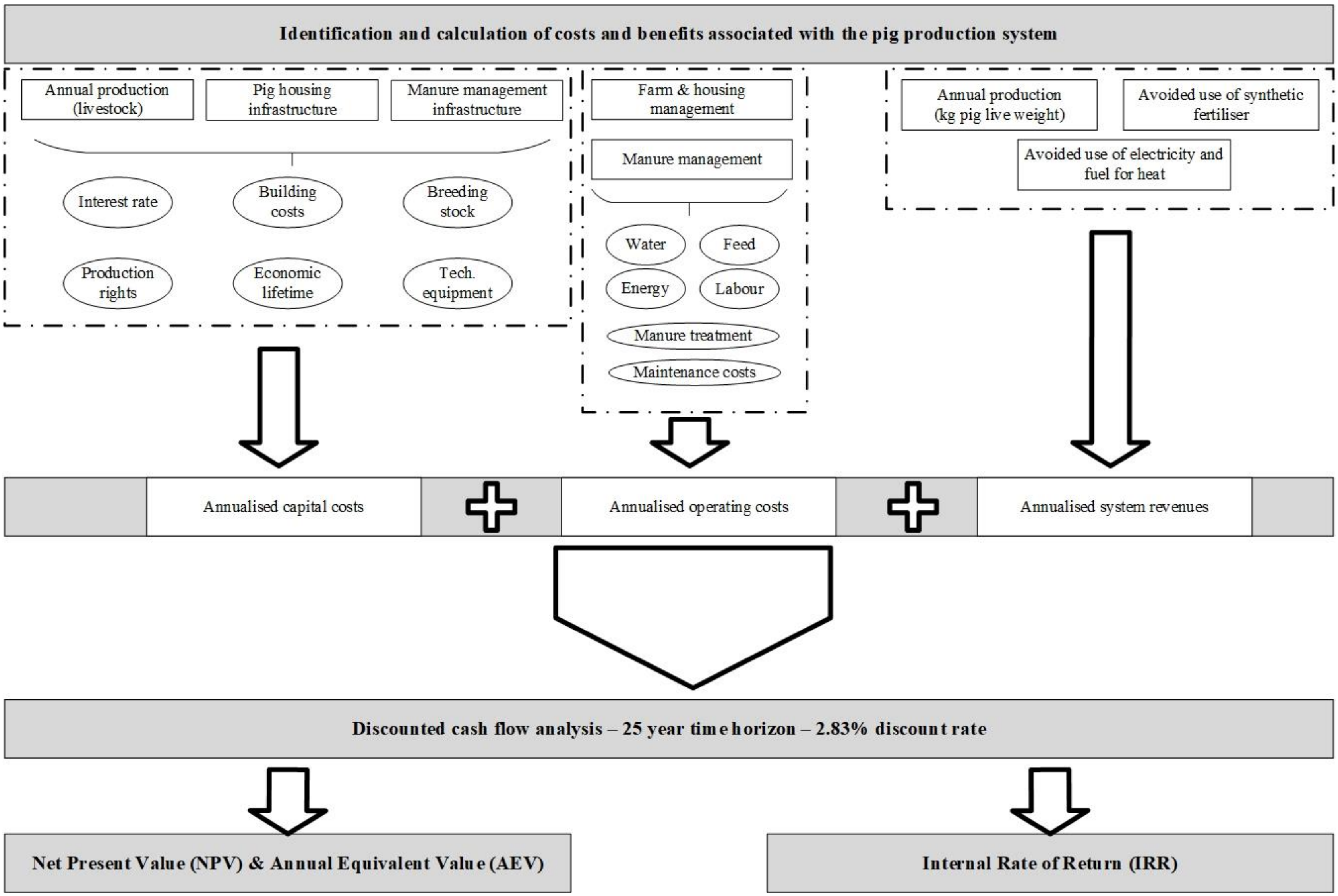


Figure 3.2: Schematic representation of the steps followed for the discounted cash flow analysis and the calculation of the net present value, annual equivalent value and internal rate of return values for all abatement measures considered in this study

3.2.5. Environmental life cycle assessment

An attributional, cradle-to-farm-gate LCA framework was constructed in SimaPro 8.5.0.0 (PRé Consultants, Amersfoort, The Netherlands) according to Pexas et al. (2020a). The model was used to describe the baseline typical integrated Danish pig farm (Section 3.2.1) and a set of abatement measures related to the housing and manure management components (Section 3.2.2). The environmental impact of the pig farming system was estimated on an annual basis (annual production). The environmental impacts assessed were selected according to the FAO guidelines for environmental impact assessment of pig supply chains (FAO, 2018):

i) *Non-Renewable Resource Use (NRRU)* expressed in *grams of antimony* (Sb) equivalents
ii) *Non-Renewable Energy Use (NREU)* expressed in *MJ*
iii) *Global Warming Potential (GWP)* expressed in *tonnes of carbon dioxide* (CO_2) equivalents
iv) *Acidification Potential (AP)* expressed in *tonnes of sulphate* (SO_2^-) equivalents
v) *Eutrophication Potential (EP)* expressed in *tonnes of phosphate* (PO_4^{3-}) equivalents.

Land occupation and water footprint impact categories were not included in the analysis due to data limitations. The abatement potential of each abatement scenario was calculated as its difference in each environmental impact when compared to the baseline (separately for each EI category). Each environmental impact category was assessed individually and the study did not aggregate across categories.

A Monte Carlo method (1000 parallel simulations for each scenario compared against the baseline) was applied for the quantification of uncertainties related to data inputs and to distinguish between uncertainties specific to each scenario or shared between scenarios. If a scenario exhibited different (lesser or greater) environmental impact than the baseline for more than 95% of iterations, the results were considered to be significantly different (Mackenzie et al., 2015; Pexas et al., 2020a). Figure 3.3 presents the main components and flows of the baseline environmental LCA along with the connection to the economic model. Costs and revenues were estimated for each process within the system boundaries, based on animal performance characteristics and farm productivity (litter size, mortality rates, energy requirements for maintenance & growth) and material flows (i.e. nutrient excretion, emissions to air, soil and water) at each production stage.

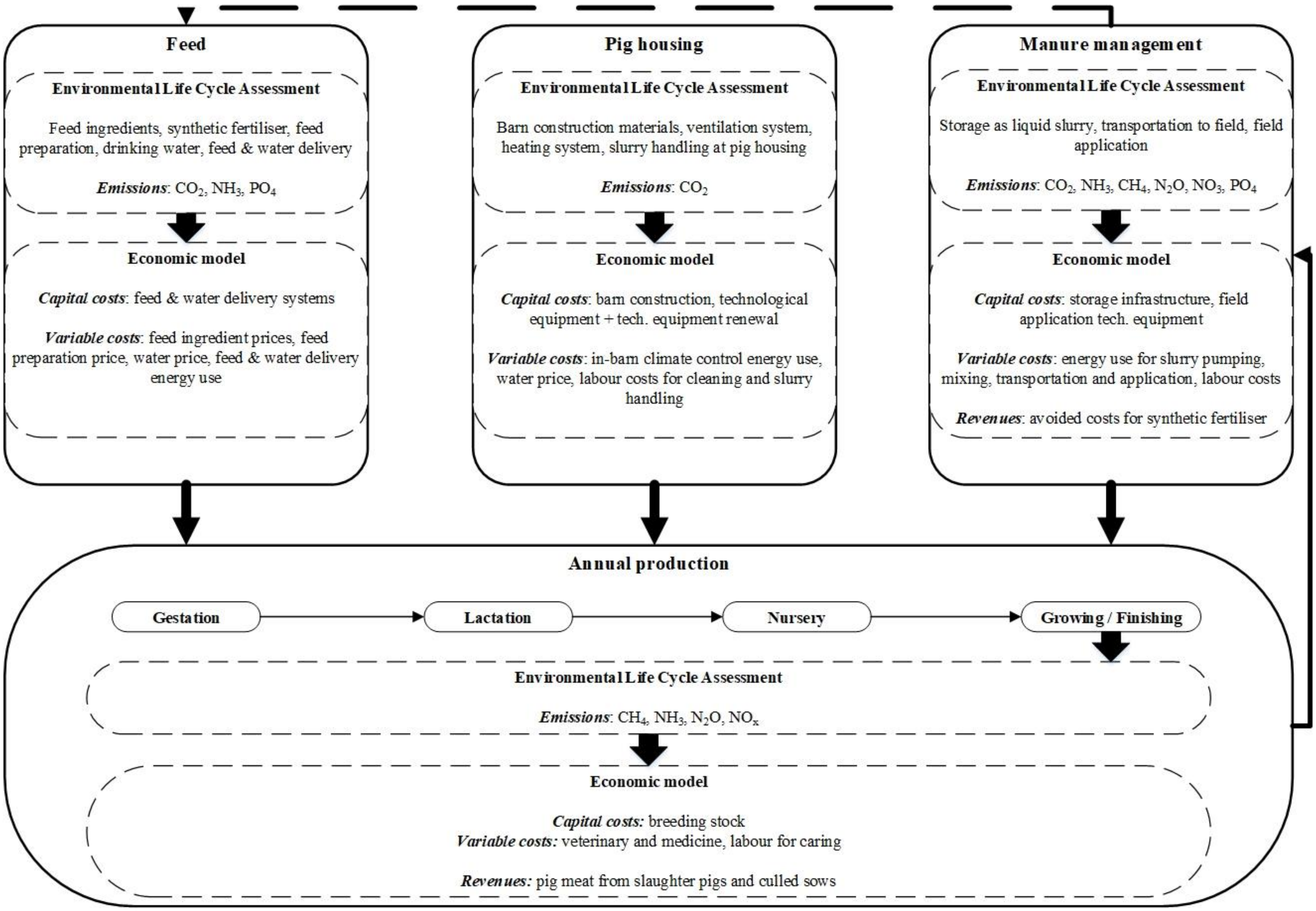


Figure 3.3: Schematic representation of the main components and flows in the baseline environmental and economic models. Solid arrows represent the direction of material and cost / benefit flows. The dashed arrow represents the replacement of synthetic fertiliser through the application of manure. We considered energy use (electricity, natural gas, diesel fuel) in all relevant processes within the system boundaries.

3.2.6. Cost-effectiveness analysis

A bottom-up, process-based, environmental abatement cost approach was adapted and used to develop EAC curves for abatement measures implemented specifically in the pig production sector and addressing specific environmental impact categories.

The cost-effectiveness of each abatement measure considered was calculated through the following equation to provide context for the construction of the EAC curves.

$$(\textbf{Eq. 3.3})\quad €\, per\ unit\ of\ pollutant\ reduced = \frac{\Delta AEV}{\Delta EI} \times -1$$

Where: *Unit of pollutant reduced:* different for each EI category assessed (i.e. tonnes of SO_2^- eq., tonnes of CO_2 eq.), *ΔAEV:* difference in annual present value between the abatement scenario and the baseline, calculated through the discounted cash flow analysis (Section 3.2.4), *ΔEI:* abatement potential of measure for the specific EI category assessed, calculated as the difference in EI compared to the baseline through the environmental LCA (Section 3.2.5).

Annual Equivalent Values were preferred over net present values for the presentation of cost-effectiveness results, to aid intuition of the findings. Within this approach, it is acknowledged that annual measures of financial performance are more commonly used and are easier to interpret by pig farm managers and other stakeholders. Cost of abatement values were reported on the EAC curves as log10-transformed values to capture the large differences exhibited and enable better visualisation.

Whenever two or more abatement scenarios were mutually exclusive or they exhibited similar cost-effectiveness, the less expensive option was assumed to be implemented first (Stokes et al., 2014). Measures that exhibited negative abatement costs can be characterised as “win – win” strategies since they enhance financial performance of the pig farming system while reducing its environmental impact.

3.3. Results

3.3.1. Discounted cash flow analysis

Table 3.3 presents whole-farm net present value, annual equivalent value and internal rate of return for the selected abatement scenarios.

Implementing stand-alone pig housing related abatement measures generated whole-farm net present values (€286,799 to €727,427) similar to the implementation of stand-alone manure management related abatement measures (€216,488 to €825,804).

The top ten combinations of abatement measures based on their annual present value (descending order) were: i) *AD & IVE*, ii) *AD & IMIN* iii) *IMIN & IVE & AD*, iv) *IVE & IMIN* v) *AD & FSR*, vi) *IVE & FSR & AD*, vii) *IVE & ISD*, viii) *IMIN & FSR & AD*, ix) *IMIN & IVE & FSR & AD* and x) *IVE & FSR*. The implementation of stand-alone slurry separation resulted in a relatively high whole-farm annual present value (€32,888). However, stand-alone slurry separation or any "pig housing–slurry separation" combinations were not further considered, because from an environmental perspective they exhibited little abatement potential and only for Non-Renewable Energy Use (~2.18% reduction compared to baseline).

The estimated annual equivalent values revealed that only four of the selected abatement scenarios were more profitable than the baseline: $AEV_{AD\ \&\ IVE}$ = €49,099, AEV_{AD} = €44,048, $AEV_{AD\ \&\ IMIN}$ = €42,903 and $AEV_{IMIN\ \&\ IVE\ \&\ AD}$ = €41,675. The implementation of any other abatement measure reduced farm profitability, with stand-alone slurry acidification generating the lowest whole-farm AEV at €11,515.

Increased ventilation efficiency and improved insulation were the most economically viable pig housing abatement measures with AEV_{IVE} = €38,693 and AEV_{IMIN} = €36,867. The least economically viable pig housing abatement measures were stand-alone modifications in slurry handling (AEV_{FSR} = €18,178 and AEV_{ISD} = €15,298). Frequent slurry removal in addition to anaerobic digestion or any other "pig housing-AD" scenario greatly reduced the profitability of the latter (~50%). However, the benefits associated with the implementation of AD overshadowed this decrease in economic performance and therefore all FSR-AD combinations remained among the most economically viable options.

Discounted cash flow analysis results for all abatement scenarios including the discarded combinations, can be found in Table A3.4 of the Appendix.

"Manure management–manure management" measure interactions (i.e. anaerobic digestion and slurry acidification combined) were not further considered, as they resulted to expensive investment scenarios that were not realistic for a 500-sow integrated pig farm. The study acknowledges that in some cases such combinations could increase the abatement potential of certain manure management technologies. “Manure management–ISD” combinations were excluded from the analyses for the same reason.

Table 3.3: Whole-farm net present value over the time horizon, whole-farm internal rate of return and whole-farm annual equivalent value for the selected abatement measures. Stand-alone implementation presented above the double, horizontal line and combinations of abatement measures presented below.

Abatement measure	**Whole-farm net present value (€)**	**Whole-farm annual equivalent value (€)**	**Whole-farm internal rate of return (%)**
Business As Usual – **BAU**	731,505	38,909	6.41
Anaerobic Digestion – **AD**	825,804	44,048	5.88
Increased Ventilation Efficiency – **IVE**	727,427	38,693	6.40
Improved Insulation – **IMIN**	693,103	36,867	6.16
Frequent Slurry Removal – **FSR**	341,746	18,178	4.56
Increased Slurry Dilution – **ISD**	286,799	15,298	4.29
Slurry Acidification – **Acid**	216,488	11,515	3.93
AD & IVE	920,492	49,099	6.21
AD & IMIN	804,328	42,903	5.76
IMIN & IVE & AD	781,303	41,675	5.68
IVE & IMIN	687,361	36,664	6.13
AD & FSR	436,045	23,259	4.49
IVE & FSR & AD	433,929	23,146	4.48
IVE & ISD	409,441	21,840	4.89

IMIN & FSR & AD	399,248	21,296	4.33
IMIN & IVE & FSR & AD	393,506	20,990	4.31
IVE & FSR	336,015	17,923	4.53

3.3.2. Environmental life cycle assessment

Pig housing related abatement scenarios under baseline manure management exhibited potential to mitigate significantly all environmental impact categories. However, their abatement potential was many times larger when they were implemented in combination with manure management related abatement measures (i.e. in the case “pig housing-anaerobic digestion” combinations for GWP mitigation) (Tables 3.4-3.5).

Stand-alone anaerobic digestion and “pig housing-anaerobic digestion” combinations achieved the largest abatement potential for NRRU and NREU, ranging from -9.67% to -14.7% and -33.5% to -40.8% respectively. Of the stand-alone pig housing related abatement measures, only increased ventilation efficiency significantly reduced both impact categories, by -1.77% and -4.60% respectively.

“Pig housing-AD” combinations exhibited the largest abatement potential also for GWP ranging from -10.4% to -11.8%, followed by stand-alone AD (-9.62%). Increased ventilation efficiency reduced GWP by -1.79% and improved insulation by -1.33%. Their abatement potential for GWP was improved when they were implemented together (-2.32%).

Regarding AP and EP, slurry acidification exhibited the largest abatement potential for both categories (-24.6% for AP and -11.4% for EP) followed by increased slurry dilution (-5.29% for AP and -0.850% for EP). Improving the insulation reduced AP by -1.40% and EP by -0.174%, and increasing ventilation efficiency mitigated AP by -0.860% and EP -0.244%. The abatement potential of the latter two was improved through their combined implementation (-1.63% for AP and -0.207% for EP).

Table 3.4: Annual environmental impact of the typical integrated Danish pig farm under baseline conditions and annual abatement potential of each stand-alone measure (as % of impact under baseline). NRRU = Non-Renewable Resource Use, GWP = Global Warming Potential, AP = Acidification Potential, NREU = Non-Renewable Energy Use, EP = Eutrophication Potential, * = non-significant difference to baseline

Impact category		Business As Usual **BAU**	Improved Insulation **IMIN** (%)	Increased Ventilation Efficiency **IVE** (%)	Frequent Slurry Removal **FSR** (%)	Increased Slurry Dilution **ISD** (%)	Anaerobic Digestion **AD** (%)	Slurry Acidification **Acid** (%)
NRRU	Mean	2,171	+0.153	-1.77	+1.29	+3.84	-14.7	+8.37
(g. Sb eq.)[7]	St. dev.	352	0.0471	0.000701	0.0840	0.870	2.37	2.29
GWP	Mean	4,927	-1.33	-1.79	-0.00762	0.348*	-3.17	+8.89
(t. CO_2 eq.)[8]	St. dev.	66.7	0.0538	0.0146	0.00434	0.0271	0.208	0.220
AP	Mean	38.6	-1.40	-0.860	-1.05	-5.29	+13.0	-24.6
(t. SO_2^- eq.)[9]	St. dev.	0.921	0.0865	0.00339	0.148	0.310	0.378	0.263
NREU	Mean	21,184	-4.37	-4.60	+0.468	+1.45	-33.5	+2.71
(GJ)[10]	St. dev.	697	0.198	0.0331	0.00761	0.0994	1.15	0.648
EP	Mean	42.0	-0.174	-0.244	-0.202	-0.850	+8.01	-11.4
(t. PO_4^{3-} eq.)[11]	St. dev.	0.583	0.0110	0.000336	0.0201	0.0503	1.53	0.895

[7] Sb = antimony
[8] CO_2 = carbon dioxide
[9] SO_2^- = sulphate
[10] GJ = giga-joules
[11] PO_4^{3-} = phosphate

Table 3.5: Annual environmental impact of the typical integrated Danish pig farm under baseline conditions and annual abatement potential of the selected combinations of abatement measures (% of impact under baseline). NRRU = Non-Renewable Resource Use, GWP = Global Warming Potential, AP = Acidification Potential, NREU = Non-Renewable Energy Use, EP = Eutrophication Potential, BAU = Business As Usual, IMIN = Improved Insulation, IVE = Increased Ventilation Efficiency, FSR = Frequent Slurry Removal, ISD = Increased Slurry Dilution, AD = Anaerobic Digestion, * = non-significant difference to baseline

Impact category		**BAU**	**IVE & ISD (%)**	**IVE & FSR (%)**	**IVE & IMIN (%)**	**AD & IVE (%)**	**AD & IMIN (%)**	**AD & FSR (%)**	**IMIN & FSR & AD (%)**	**IMIN & IVE & AD (%)**	**IMIN & IVE & FSR & AD (%)**	**IVE & FSR & AD (%)**
NRRU	Mean	2,171	+6.25	-0.814	-2.16	-12.1	-11.4	-9.67	-13.8	-13.2	-14.7	-12.6
(g. Sb eq.)[12]	St. dev.	352	0.824	0.0537	0.0502	2.51	2.45	2.33	2.42	2.53	2.42	2.43
GWP	Mean	4,927	-0.540*	-1.14	-2.32	-4.19	-4.36	-3.04	-4.38	-5.59	-5.24	-4.06
(t. CO_2 eq.)[13]	St. dev.	66.7	0.0375	0.0143	0.0626	0.205	0.191	0.212	0.181	0.180	0.188	0.193
AP	Mean	38.6	-5.25	-1.15	-1.63	+12.2	+11.4	+11.9	+10.5	+11.1	+10.8	+11.4
(t. SO_2^- eq.)[14]	St. dev.	0.921	0.305	0.137	0.100	0.347	0.359	0.349	0.344	0.344	0.334	0.329
NREU	Mean	21,184	-0.515	-2.14	-6.58	-35.8	-38.3	-33.6	-38.4	-40.8	-40.6	-35.8
(GJ)[15]	St. dev.	697	0.120	0.0327	0.223	0.494	0.386	0.550	0.385	0.388	0.385	0.475
EP	Mean	42.0	-0.678	-0.196	-0.207	+7.84	+8.00	+8.19	+8.33	+7.72	+8.28	+7.89
(t. PO_4^{3-} eq.)[16]	St. dev.	0.583	0.0447	0.0200	0.0134	0.216	0.223	0.226	0.692	0.211	0.333	0.218

[12] Sb = antimony
[13] CO_2 = carbon dioxide
[14] SO_2^- = sulphate
[15] GJ = giga-joules
[16] PO_4^{3-} = phosphate

3.3.3. Cost-effectiveness

Increasing ventilation efficiency and improving the barn insulation in combination with anaerobic digestion were the most cost-effective options for NRRU and NREU mitigation, with costs of abatement ranging from -€0.146 to -€0.0326 per g Sb eq. and -€1.75^{-04} to -€3.55 E-05 per GJ mitigated respectively. Stand-alone anaerobic digestion also generated a negative cost (profit) of -€0.0493 per g of Sb eq. and -€1.00 E-04 per GJ for NRRU and NREU mitigation respectively. All other abatement scenarios exhibited positive costs that ranged from €0.147 to €67.6 per g Sb eq. and €2.29 E-04 to €1.44 per GJ abated. Combinations of increased ventilation efficiency with slurry handling practices ranked as the least cost-effective, exhibiting the largest abatement costs and little abatement potential for NRRU and NREU (Fig. 3.4-3.5).

"Pig housing-AD" combinations also ranked high in cost-effectiveness for GWP mitigation with abatement costs ranging from -€0.237 to -€0.0350 per tonne CO_2 eq. abated (Fig. 3.6). Implementing stand-alone AD generated an abatement cost of -€0.206 per tonne of CO_2 eq. abated. The implementation of any other measure incurred positive abatement costs that ranged from €0.0279 to €148,077 per tonne CO_2 eq. mitigated.

For the mitigation of AP and EP, all scenarios generated positive abatement costs (Fig. 3.7-3.8). Slurry acidification was the most cost-effective option with an abatement cost of €303 per tonne SO_2^- eq. for AP and €1,190 per tonne PO_4^{3-} eq. abated for EP. Although slurry dilution exhibited large abatement potential for both impact categories, it was identified as less cost-effective than other pig housing related abatement scenarios, generating €4,174 per tonne SO_2^- eq. and €186,032 per tonne PO_4^{3-} eq. abated.

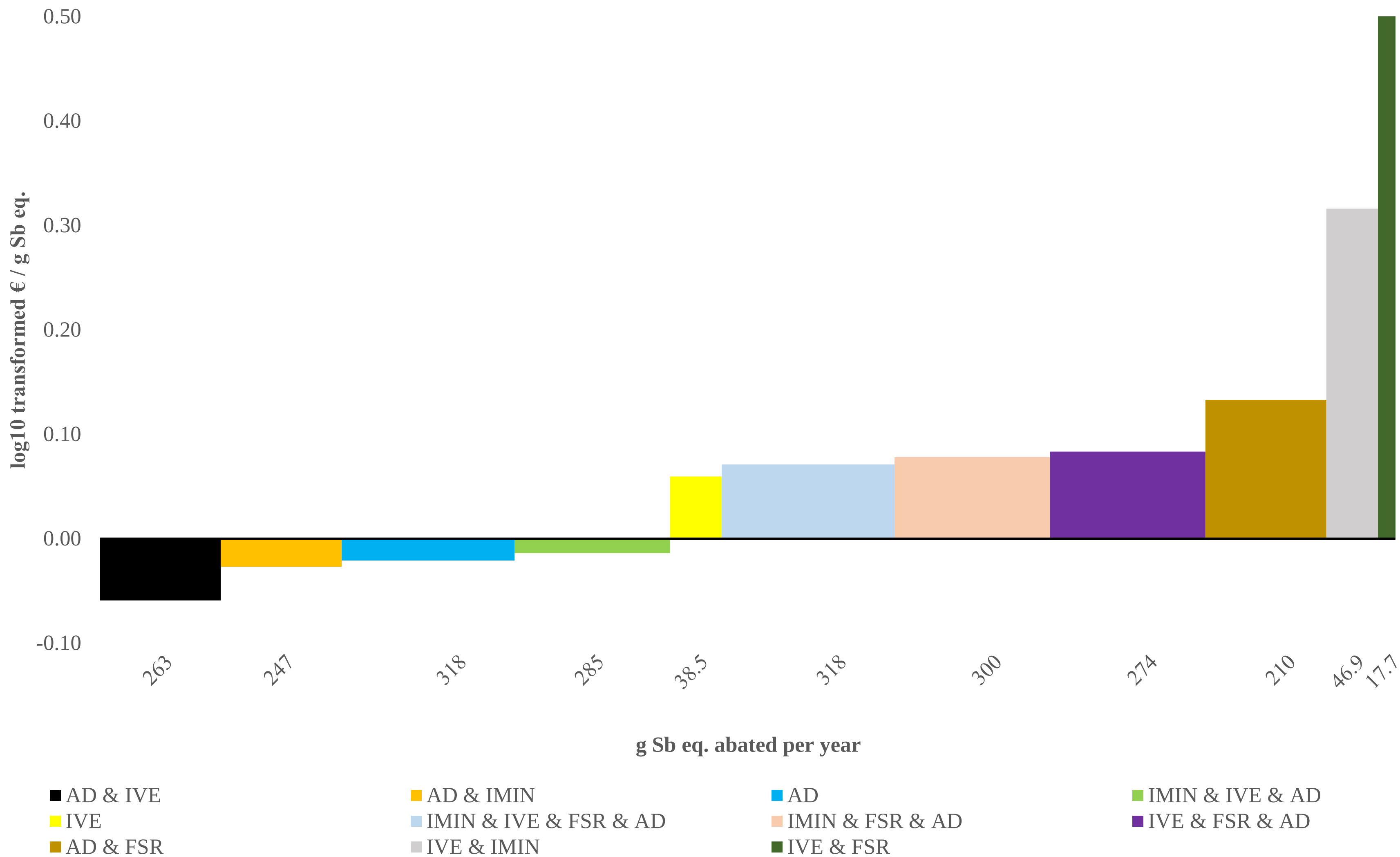


Figure 3.4: Cost of abatement for mitigation of Non-Renewable Resource Use, expressed in log10-transformed euros per g of antimony equivalents (g Sb eq.) to capture the large differences in a single curve (y-axis). The x-axis presents the annual abatement potential of each measure considered. IMIN = improved insulation, IVE = increased ventilation efficiency, FSR = frequent slurry removal, AD = anaerobic digestion

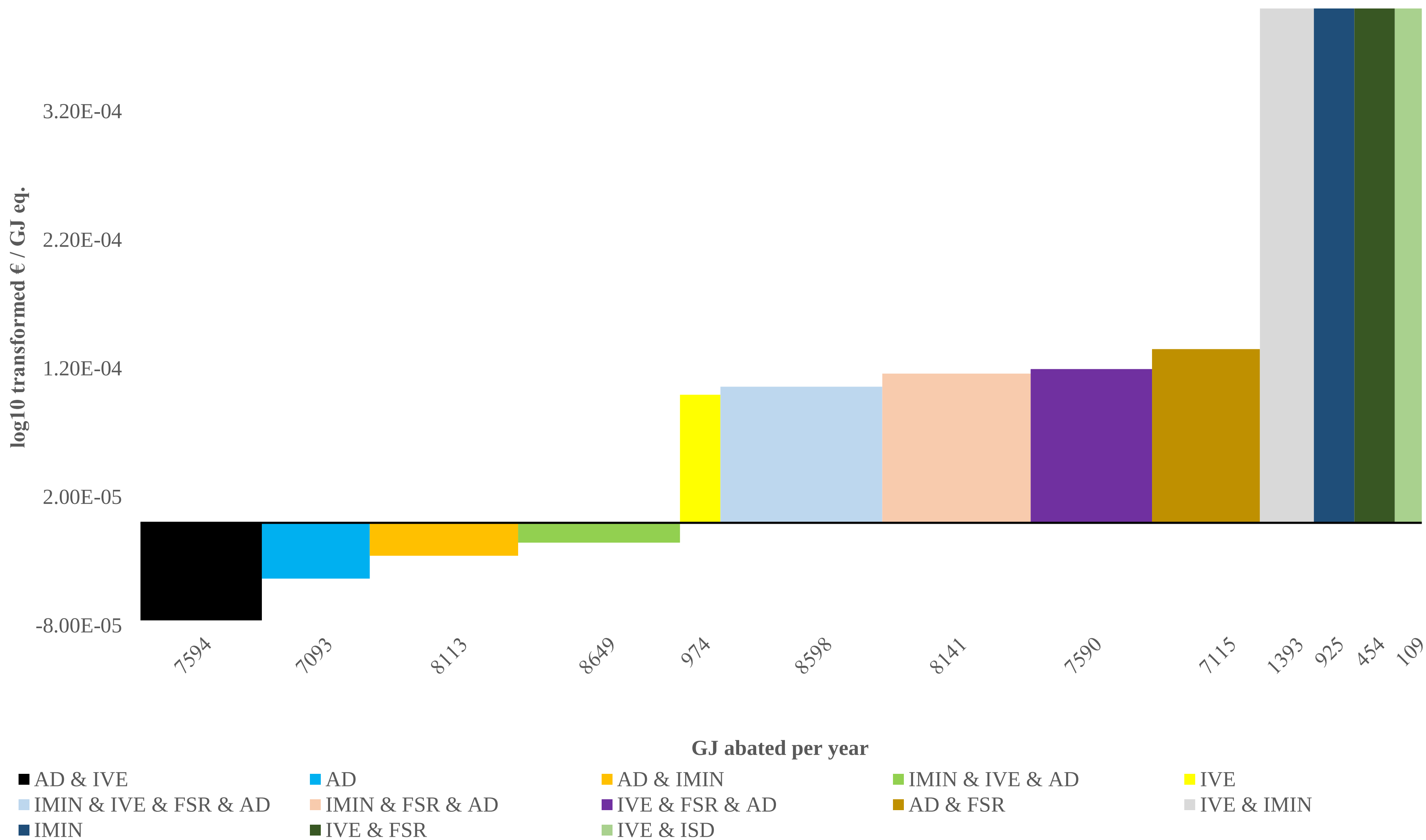


Figure 3.5: Cost of abatement for mitigation of Non-Renewable Energy Use, expressed in log10-transformed euros per gigajoules (GJ) to capture the large differences in a single curve (y-axis). The x-axis presents the annual abatement potential of each measure considered. IMIN = improved insulation, IVE = increased ventilation efficiency, FSR = frequent slurry removal, ISD = increased slurry dilution, AD = anaerobic digestion

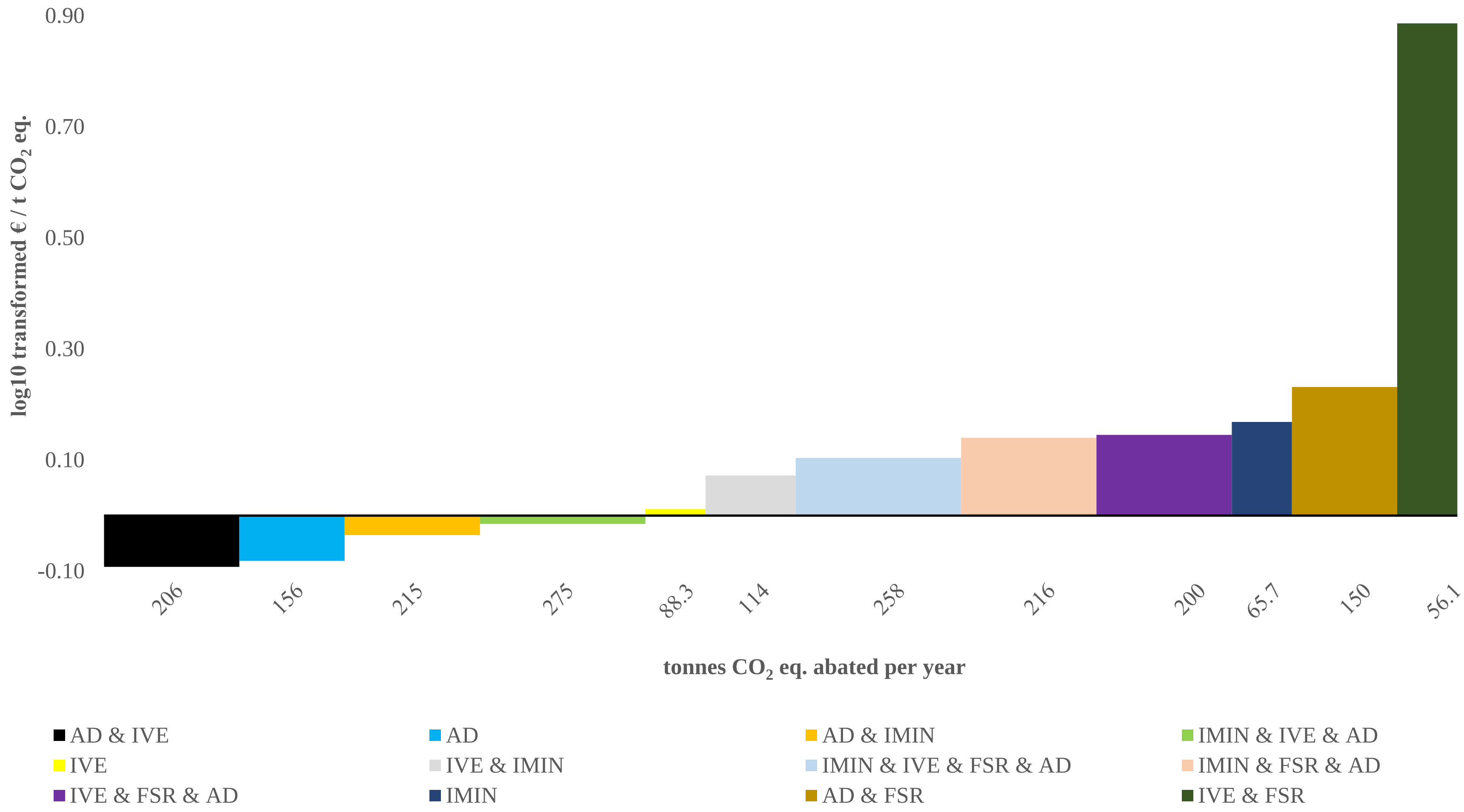


Figure 3.6: Cost of abatement for mitigation of Global Warming Potential, expressed in log10-transformed euros per tonne of carbon dioxide equivalents (tonnes CO_2 eq.) to capture the large differences in a single curve (y-axis). The x-axis presents the annual abatement potential of each measure considered. IMIN = improved insulation, IVE = increased ventilation efficiency, FSR = frequent slurry removal, AD = anaerobic digestion

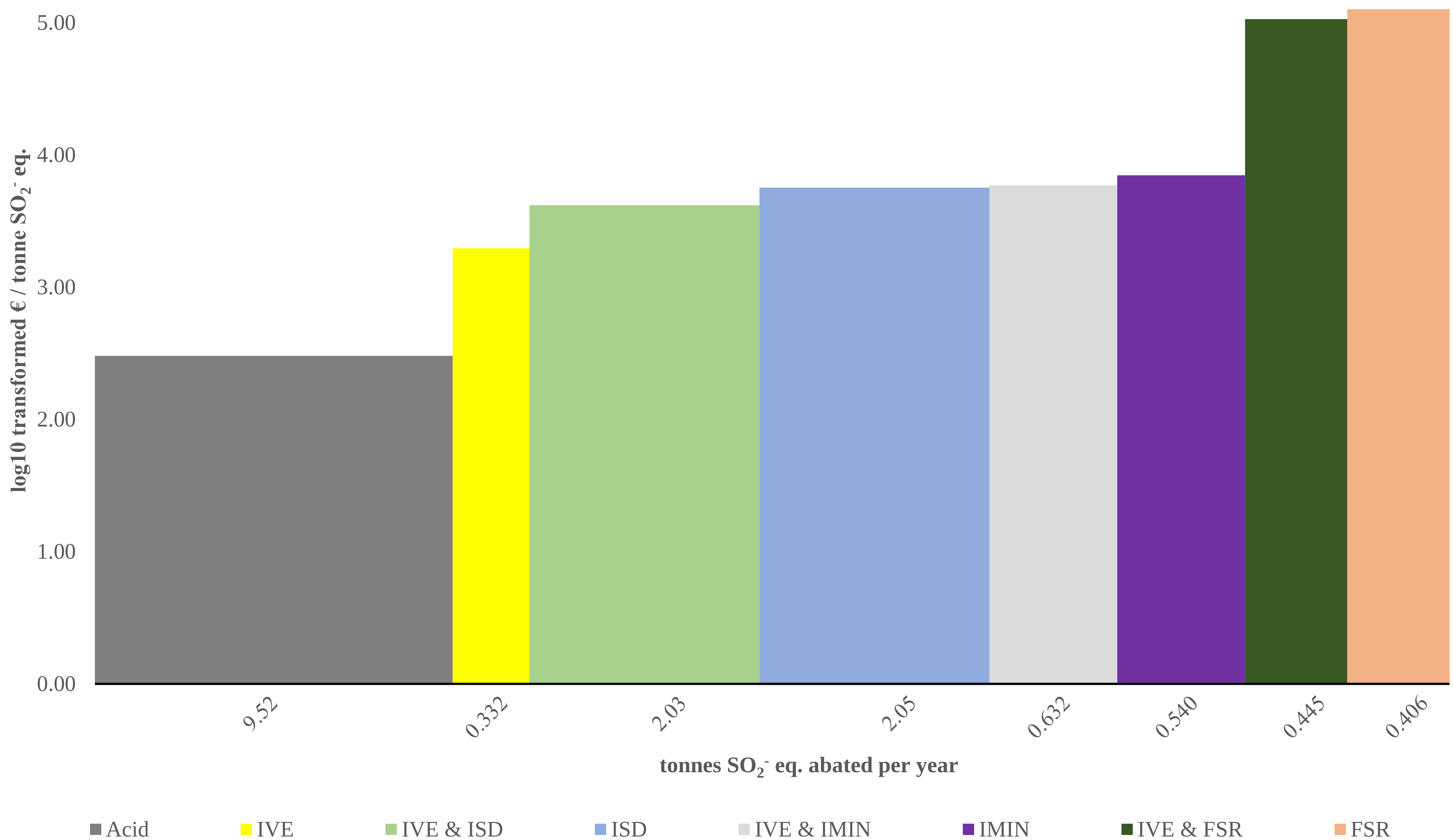


Figure 3.7: Cost of abatement for mitigation of Acidification Potential, expressed in log10-transformed euros per tonne of sulphur dioxide equivalents (tonnes SO_2^- eq.) to capture the large differences in a single curve (y-axis). The x-axis presents the annual abatement potential of each measure considered. IMIN = improved insulation, IVE = increased ventilation efficiency, FSR = frequent slurry removal, ISD = increased slurry dilution, Acid = slurry acidification

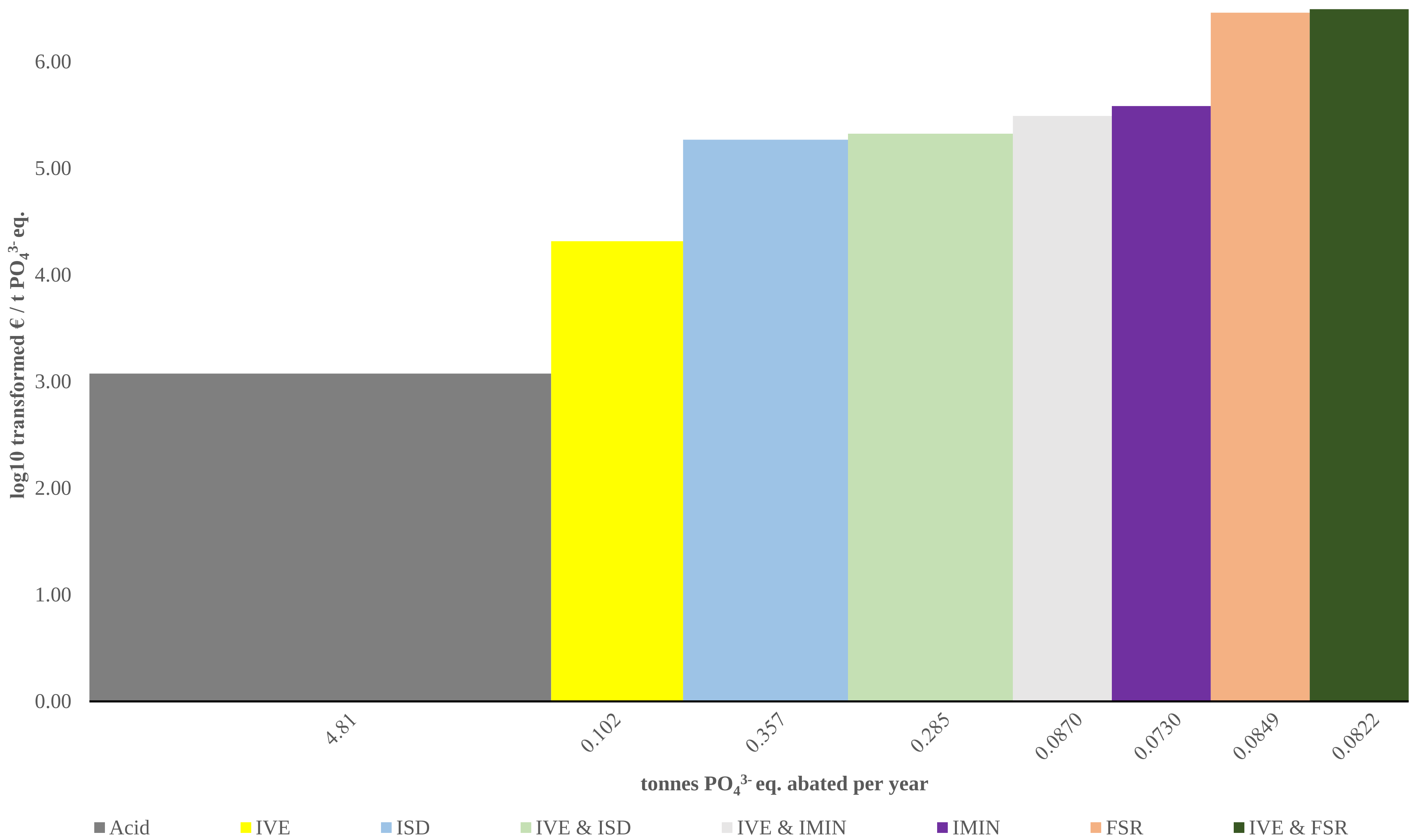


Figure 3.8: Cost of abatement for mitigation of Eutrophication Potential, expressed in log10-transformed euros per tonne of phosphate equivalents (tonnes PO_4 eq.) to capture the large differences in a single curve (y-axis). The x-axis presents the annual abatement potential of each measure considered. IMIN = improved insulation, IVE = increased ventilation efficiency, FSR = frequent slurry removal, ISD = increased slurry dilution, Acid = slurry acidification

3.4. Discussion

While previous studies have evaluated environmental impacts arising from alternative housing and manure management strategies in pig production (Cherubini et al., 2015; Philippe & Nicks; 2015 Ten Hoeve et al., 2014) less focus has been given on the assessment of the intersection between environmental impact mitigation and economic costs. The overarching aim of this study was the development of a framework that can evaluate both the environmental and economic consequences associated with changes to housing and manure management in pig production systems, from a whole-farm perspective. Further to this, the study demonstrated the framework capabilities to account for modifications in specific components of the pig farming systems and serve as a tool, which can guide decision making regarding investments that can help reduce the system environmental impact. Evaluating potential abatement measures through the context of a cost-effectiveness assessment that addresses uncertainties around their environmental performance, captures costs and benefits associated with their implementation and accounts for interaction between these two aspects, contributes to knowledge for the improvement of sustainability in pig production.

In the development of this framework, specific limitations were encountered and the study unavoidably resorted to a number of assumptions. Undoubtedly, the biggest issue was that of data availability, particularly concerning economic information. Consulting the expert opinion of researchers from the Danish Pig Research Centre (SEGES) was crucial in order to deal with such limitations. The public availability of further data would allow for the development of a stochastic economic model and account for risks associated with variability in costs and benefits over the time horizon of the analysis.

3.4.1. Cost-effectiveness of the selected abatement scenarios

Many of the mitigation strategies tested in this study, exhibited sizeable abatement potential for specific environmental impact categories but also generated large abatement costs, which suggests the importance of thorough cost-effectiveness assessment of the potential investments prior to their implementation.

For the mitigation of AP and EP, all of the abatement scenarios tested incurred costs that were many times larger than abatement costs associated with the reduction of other impact categories. For slurry acidification, the most cost-effective option for the mitigation of AP and EP also approved as a Best Available Technology for Danish standards (Kai et al., 2008; Santonja et al., 2017), such large costs could be attributed to the high capital and operating expenses associated with its implementation, especially in relation to scale of a typical Danish pig farming system (500-sow herd). In addition to such economic implications, volatile compounds that are formed through slurry acidification may have adverse effects on animal health, eco-toxicity and human toxicity (Santonja et al., 2017; Saue & Tamm, 2018), which were not captured within the presented framework. While sulphuric acid was assumed as the agent for acidification in this study, there is a variety of commercially available acids that can also reduce AP even at a lower cost, but might have adverse impacts on ecosystem, animal and human health (Borst, 2001; Saue & Tamm, 2018). It is important that the effectiveness of these options is explored prior to the implementation of slurry acidification (SEGES, 2015; Saue & Tamm, 2018).

In regards to slurry handling practices at pig housing, the findings are in agreement with previous reports on the best available techniques for rearing pigs (Santonja et al.,2017). Increasing the level of slurry dilution also showed high abatement potential for AP and EP, but poor economic performance for the system under study. This was attributed mainly to costs associated with extra amounts of water used for dilution and additional fuel for transportation of the more voluminous, diluted slurry. However, if this strategy could be achieved as a side effect of another pig housing management process (i.e. pig cooling strategies with showers) (Jeppsson et al., 2018), therefore sharing the economic consequences (costs allocated between both strategies), its cost-effectiveness could be improved and the environmental benefits would potentially outweigh the financial costs.

Implementing a frequent slurry removal regime exhibited potential to significantly reduce AP and EP. However, the incurred costs for the increase in manual labour and electricity for the operation of the slurry pumping system resulted in a low cost-effectiveness. This strategy could potentially provide a cost-effective method to reduce AP and EP, using a more efficient slurry pumping system and low-energy machinery instead of manual labour for the removal of slurry from the pens.

An opposite trend was observed for investments related to modifications in pig housing, such as increasing the ventilation efficiency or improving the barn insulation and their combined implementation. Although these strategies were not associated with particularly large reductions in the system environmental impact, their low cost of implementation enabled them to be ranked among the most cost-effective abatement measures for a variety of impact categories. For IVE, the main costs were associated with an increase in the maintenance of the ventilation system and surrounding pig housing elements, while it was the price difference between the different insulation materials installed for IMIN. In both cases, investing in more efficient, long-lasting technological equipment and construction materials could increase their cost-effectiveness even more. Although to a lesser extent than modifications in slurry handling or manure management, abatement measures related to barn construction and indoor climate control can open an avenue for action when targeting the improved sustainability of the system.

The most cost-effective strategies for GWP, NRRU and NREU were related to the implementation of on-farm anaerobic digestion of slurry. The cost-effectiveness of such high investments can be sensitive to economic parameters that change over time and with location and therefore, it is important that assessments prior to their implementation use up-to-date data and account for uncertainties wherever possible (Redman, 2010). The study acknowledges that AD at central facilities is a rapidly expanding strategy, currently preferred by smaller farms in Denmark as opposed to on-farm AD. However, this was a particularly complex strategy to simulate and predict within a cost-effectiveness assessment, compared to the more straightforward on-farm AD (Al Seadi, 2017). Despite the high cost of implementation for on-farm AD, the benefits it yields through the production of electricity and heat (discounted on-farm electricity use) and the application of a nutrient-rich digestate with improved fertiliser properties (Santonja et al., 2017), classify it as the most cost-effective mitigation strategy in this study. In fact, these benefits outweighed the poor economic performance of pig housing related abatement measures like the FSR and even the combinations between FSR-AD were among the most cost-effective options identified in this chapter.

Important trade-offs were identified between the EI categories assessed associated with the implementation of several of the abatement measures. While implementing anaerobic digestion and its combinations largely reduce GWP, NREU and NRRU, they also led to a significant increase in AP and EP due to the nutrient rich digestate applied as fertiliser in the fields. The opposite effect was observed when implementing abatement scenarios with slurry acidification and slurry dilution. These environmental mitigation practices mainly targeted the reduction of AP and EP, but caused large increases in NRRU.

3.4.2. Methodological challenges

Within the framework presented in this study, a discounted cash flow model was merged with an environmental LCA model of pig farming systems to develop EAC curves for different environmental impact categories. In doing so, large uncertainties that exist within the LCA model were acknowledged and accounted for by following established methods for scenario comparisons (Leinonen et al, 2012; Mackenzie et al, 2015). While EAC and similar methods such as Marginal Abatement Cost (MAC) analysis are driven by deterministic economic models, it is clear that cost and revenue streams within the systems modelled are not static. Eory et al. (2018) have recently looked to address this by presenting simplified conceptual representations of the uncertainty in both the environmental and economic aspects of a MAC framework for Scottish agriculture. Addressing qualitative economic uncertainties as described by Eory et al. (2018) (i.e. farmer behaviour, agri-environmental policy), would allow for a more comprehensive assessment of the applicability and of a potential farm investment, which would eventually affect its cost-effectiveness. This is an avenue for improvement of environmental abatement cost analyses and important to consider, particularly when evaluating long-term investments that are related to many stakeholders, as for the case of on-farm AD in this study.

While the developed framework can effectively summarise the environmental and economic performance of a potential abatement measure in one score for a specific EI under assessment, the study did not attempt to merge multiple environmental mitigation objectives into a single composite measure. Identifying the most cost-effective abatement measure over a range of EI categories is a process sensitive to the weighting factors assigned to each of the impact categories (Garcia-Launay et al., 2018). In this study, each EI category was addressed individually. Weighting factors were not assigned nor EIs aggregated across impact categories, in order to provide a pragmatic option for the decision making process. The existence of several weighting options is acknowledged, i.e. based on public opinion and monetary valuation (Bengtsson & Steen, 2000; Soares, Toffoletto & Deschênes, 2006). However, the study considers the weighting of impacts a subject more appropriately addressed by decision makers in the application of the framework presented here, rather than the core focus of this study.

3.4.3. Policy implications

A robust assessment of the environmental and socio-economic impacts of production systems is the basis for cohesive policy, business and consumer decision making (Hellweg & Canals, 2014). Although Danish pig production was used in this study as a case in point, the results have broader implications in driving policy-making regarding the improved sustainability of various agricultural sectors and for many countries / regions.

Through the more focused study presented here, some of the key challenges that policy makers face when targeting the improved sustainability of the pig supply chain were identified. While cost-effectiveness provides a meaningful and easy to interpret indicator that can help guide investment strategies for the reduction of specific environmental impacts, decision-making is largely dependent on the environmental mitigation targets set by the stakeholders in each agricultural sector (Eory et al., 2018). The study highlights that in order to mitigate GWP and NRRU in a cost-effective manner, more expensive investments were required, as for example with the implementation of on-farm anaerobic digestion. Policy mechanisms that financially support the realisation of such large investments should be in place if the priority is to mitigate greenhouse gas emissions that contribute to GWP and the depletion of abiotic resources.

Geography can also play an important role in guiding actions for the improved sustainability of pig production systems and in shaping policies for the sector (Olander, Wollenberg, Tubiello & Herold, 2013). The density of pig farming units for example might affect the feasibility and profitability of certain types of investments (e.g. anaerobic digestion in centralised facilities) (Ciroth, Hagelüken, Sonnemann, Castells & Fleischer, 2002). Regional differences in management practices, physical geography and economic status should be considered when cost-effectiveness assessments are used to guide policy-making on a broader spatial extent. This study describes a cost-effectiveness assessment framework for farm level sustainability assessments. Geographic differences on a broader scale could be evaluated through regional assessment tools, perhaps with the integration of geographical information system models in life cycle and cost-effectiveness assessments.

3.5. Conclusions

In this chapter, a whole-farm, cost-effectiveness assessment framework addressing a European pig farming system was presented. Its capabilities to guide decision making regarding investments at pig housing and manure management that target reductions in the system environmental impact were demonstrated. The results suggest that the implementation of on-farm anaerobic digestion as a stand-alone investment, or through its combination with pig housing related modifications (i.e. increased ventilation efficiency, improved barn insulation), were the most cost-effective options to reduce global warming potential, non-renewable resource use and non-renewable energy use. The most cost-effective investments for the mitigation of acidification and eutrophication potential were slurry acidification and the less expensive increased ventilation efficiency. Reducing global warming potential, non-renewable resource use and non-renewable energy use required the implementation of more expensive investments than for acidification and eutrophication potential. The findings suggest that there are no “silver bullet” solutions when targeting the improved environmental and economic performance of a pig farming system. However, several “win-win” strategies were identified that can enhance farm profitability while also achieving sizeable environmental abatement potential.

Chapter 4. Environmental and economic consequences of pig-cooling strategies implemented in a European pig-fattening unit

Abstract

The increased frequency of hot days due to climate change can potentially impair the environmental and economic performance of pig-fattening farms. Several pig-cooling strategies have been proposed to address these impacts, however their implementation is not always economically viable and the potential environmental-economic trade-offs not well understood.

This study proposes and implements a novel framework for environmental and economic evaluation of pig-cooling strategies in a whole farm context. It also demonstrates, through a sensitivity analysis, how such models can be integrated with projected climate data to investigate how climate change may affect the assessment of capital investments that are made over significant timescales. Two strategies implemented in a pig-fattening farm in south Sweden were considered: pig-cooling with showers and with increased air velocity. Operation of the farm under non-cooling conditions was considered as the baseline system against which the analysis was conducted. The whole-farm AEV was calculated with the implementation of each strategy through a discounted cash flow analysis and annualised system environmental impact through a life cycle assessment.

Both cooling strategies significantly reduced system environmental impact across all categories except water footprint. Acidification potential was reduced the most, exhibiting a -3.28% reduction with pig showers and -1.51% with increased air velocity. Farm profitability improved by +6.79% with showers and +3.37% with increased air velocity. Ambient temperature increase under non-cooling conditions significantly increased all impact categories with acidification being affected the most (+2.24%), and caused a -4.43% decrease in AEV. Both pig-cooling strategies mitigated these effects on system environmental performance. With increased air velocity we observed a +0.718% increase in acidification, while pig showers were the more resilient option exhibiting a +0.690% increase.

The study represents a case-in-point for how to rationalise economically environmental management technologies in pig housing systems based on their cost-effectiveness in mitigating environmental impacts.

4.1. Introduction

European pig production predominantly occurs in large-scale units controlled by mechanically ventilated and well-insulated buildings (Gerber et al., 2013). Due to the high heat load produced by the animals over the summer period, indoor temperature and humidity in such systems can reach high levels similar to those of tropical conditions even when the farm is located in temperate climatic zones (Schauberger et al., 2019). Evidence in literature suggests that prolonged hot (>27 °C) and humid environmental conditions have direct consequences on animal productivity with reported reductions in growth rate (-38.7%) and feed intake (-17.2%) of growing and finishing pigs for the duration of such environmental conditions (Myer & Bucklin, 2001; Wellock et al., 2003; Huynh et al., 2006).

Pig production is regarded among the largest contributors to acidification of ecosystems and eutrophication of fresh water bodies, arising from livestock (De Vries & De Boer, 2010). Suboptimal farm productivity under 'hot' conditions can potentially increase the system environmental impact as it is associated with inefficient use of resources such as on-farm energy and feed use (Gerber et al., 2013). An increase in ambient temperature, can also significantly affect ammonia emissions at the pig housing and manure management component (Rigolot et al., 2010; Pexas et al., 2020a). Potential economic losses associated with the impaired performance of animals in pig farming systems have also been previously identified. Farm profitability can be significantly impacted by heat stress, since the feed and pig meat are major costs and revenues respectively (St-Pierre, Cobanov & Schnitkey, 2003; Dittrich, Wreford, Topp, Eory, & Moran, 2017; Hoste, 2017). System economy can also be impacted by variations in the efficiency (nitrogen, phosphorus, potassium concentration) of manure as an organic fertiliser (Pexas, Mackenzie, Wallace & Kyriazakis, 2020b).

Several alternative management strategies and technologies have been proposed to tackle the effect of increased ambient temperature on animal performance and emissions at pig housing (Vitt et al., 2017; Mikovits et al., 2019). Among the practices that can potentially achieve combined benefits for mitigation of heat stress and ammonia emissions, is cooling of the pigs (Botermans, Gustafsson, Jeppsson, Brown & Rodhe, 2010). During hot periods, pigs alter their behaviour to combat heat stress and tend to lie in the slatted, excretory area of the pen, increasing fouling in the solid, lying area. Consequently, ammonia emissions at pig housing increase due to the larger surface of manure exposed to air and high temperature (Aarnink, Schrama, Heetkamp, Stefanowska & Huynh, 2006). Increased air velocity at pig lying area affects the immediate thermal vicinity of the animals, causing increased convective heat losses from their bodies and therefore expanding the thresholds of their perceived thermo-neutral zone (wind-chill effect) (Wellock et al., 2003; Zhang & Bjerg, 2017). Cooling can also be achieved with frequent showers over the slatted area of the pen during 'hot' periods. This way, animals lie less in the excretory area and pen cleanliness is improved. Furthermore, evaporative cooling is increased from pig wet skin, which can potentially reduce the effect of heat stress (Wellock et al., 2003; Aarnink et al., 2006; Huynh et al., 2006). The implementation of such cooling strategies has direct (i.e. slurry dilution from showers) and indirect effects (i.e. more nitrogen in manure due to reduced NH3 emissions) on manure composition. Therefore, to evaluate their environmental performance accurately we should adopt a whole-farm approach, considering interactions between all system components (Pexas et al., 2020a).

Pig-cooling strategies can also increase farm related costs (i.e. investment in technological equipment, running costs) and so thorough cost-effectiveness assessments should be performed prior to their implementation (Mikovits et al., 2019, Pexas et al., 2020b). Some studies have attempted to evaluate the effectiveness of similar strategies to improve farm economic performance and animal welfare conditions at growing and finishing pig farming systems (Vitt et al., 2017; Schauberger et al., 2019).

With an increase in ambient temperature and the frequency of hot days due to climate change, the resilience of confined pig farming systems to heat stress, as well as the mitigation of their potential environmental and economic impacts are of increasing concern (Valiño, Perdigones, Iglesias & García, 2010; Beniston, Stoffel, & Guillet, 2017; Mikovits et al., 2019). In this study, a gap in existing whole-farm environmental impact assessments of pig farming systems under heat stress conditions was addressed. For the first time, the potential environmental and economic impact trade-offs associated with the implementation of pig-cooling strategies that target heat stress and ammonia emissions mitigation in a European pig-fattening unit were evaluated. The implications of projected ambient temperature increases for Sweden caused by global heating on the environmental impact mitigation provided by pig-cooling scenarios were also investigated. In doing so, the study demonstrates a novel framework for farm level environmental and economic evaluation of animal housing technologies that can be integrated with projected to provide insight as to how global heating may affect the cost-effectiveness of capital investments based on their potential to mitigate environmental impacts in the long term.

4.2. Materials and Methods

The primary aim of this study was to evaluate trade-offs in the environmental impacts and economic implications associated with the implementation of pig-cooling strategies that target ammonia emission reductions at a pig-fattening unit. To achieve this aim the specific steps below were followed:

i) The pig production system under assessment was described and the indoor climate, animal growth and heat stress related parameters were modelled as a function of outdoor climate data and specific to the system, climate control properties.

ii) Scenarios were developed to simulate the operation of the pig production system with the implementation of two pig-cooling strategies: (1) cooling with showers over the slatted pen area and (2) cooling with increased air velocity at the pig lying area. These strategies were contrasted with a baseline ('non-cooling conditions') comprising a standard management system without novel cooling technologies deployed.

iii) The annualised system environmental impact was estimated for each scenario, through an environmental life cycle assessment framework.

iv) The financial performance of each scenario was estimated using whole-farm annual equivalent values derived from a discounted cash flow analysis over a 25-year time horizon.

v) The potential environmental and economic trade-offs were evaluated by assessing the cost-effectiveness of each pig-cooling strategy in reducing system environmental impact.

vi) A sensitivity analysis was performed to estimate the effect of climate change as an increase in ambient temperature on the system environmental and economic performance under varied cooling conditions.

4.2.1. Description of the study area and pig farming system

Analyses were performed on a typical pig-fattening unit for Sweden, located near Malmö, southern Sweden (55.6050° N, 13.0038° E). The case study was purposefully selected as it demonstrates how projections for increased temperatures across all seasons may indicate the need for animal cooling even in places where it was not traditionally used (Ruosteenoja, Markkanen &

Räisänen, 2020), and on the basis of data availability regarding the effect of pig cooling on ammonia emissions at housing. Although Sweden is located in northern Europe, its climate is similar to that of the largest part of Central Europe, where a big portion of pig production takes place (Vitt et al., 2017; Mikovits et al., 2019). The specific climatic type is temperate, with summers characterised by warm temperatures and moderate humidity (Cfb type according to Köppen-Geiger climate classification). Relevant data to describe the system under assessment were obtained from the Swedish University of Agricultural Sciences (SLU), and from published reports on the specifications for pig-fattening units by the Swedish Board of Agriculture (Swedish Board of Agriculture, 2018). The unit reared pigs for approximately 90 days and completed an average of three production cycles per year. Animals reared in the pig farming system were offspring of Topigs Norsvin 70 sows x Hampshire sires. They entered the fattening unit at 30 kg and under normal climate and management conditions, they reached an approximate slaughter weight of 115 kg. Farm production capacity was 1320 animals per batch with equal number of entire males and females.

Pig housing comprised a barn of six rooms (23.5 m length x 11.6 m width x 3 m height per room) with 120 pens (20 per room) accommodating an average of 11 pigs per pen. The building consisted of concrete walls, well-insulated with polyurethane boards, a flat ceiling insulated with fiberglass, concrete partially slatted floors (30% slatted: 70% solid) and under-barn slurry pits, complying with the Best Available Techniques guidelines for rearing of pigs (Santonja et al., 2017). Cleaning, disinfecting and barn preparation activities occurred at the end of each production cycle and lasted four days; the building remained unoccupied during this period. Manure was stored outside in concrete, covered slurry tanks and applied by trail-hose tanker to replace synthetic fertiliser for crop production. The amount of manure applied as organic fertiliser was estimated based on nutrient substitution rates, which were assumed to be 75% for nitrogen, 97% for phosphorus and 100% for potassium, representing the national average (Nguyen et al., 2011). Although derived from modelling of Danish pig systems, these figures represent the best estimates with respect to pig systems in Northern Europe for implementing the convention of accounting for mineral fertiliser replacement in LCA through system expansion (Hanserud, Cherubini, Øgaard, Müller & Brattebø, 2018).

4.2.2. Indoor climate modelling

Indoor climate conditions were regulated by a low-pressure ventilation system (SKOV LPV system). To estimate indoor climate parameters relevant to the system environmental and economic impact for any given day in production (indoor temperature and ventilation rate), the sensible heat balance principle $s_A + s_B + s_V = 0$ was used (Schauberger et al., 2000). In the model, S_A represents the sensible heat release from the animal calculated as a function of animal body mass. S_B is the sensible heat loss due to transmission through the building calculated as a function of insulation, building surface and indoor-outdoor temperature differential. S_V is the sensible heat flow due to the ventilation system calculated as a function of the indoor-outdoor temperature differential and climate control system properties (i.e. minimum & maximum ventilation rates). Temperature set points for the specific climate control system ranged from 19.4 ℃ in the first week of production to 16.5 ℃ before the animals reached slaughter weight. The unoccupied barn was heated prior to animal introduction and therefore, the starting temperature was 19.4 ℃ on the first day production. Indoor temperature and ventilation rate for a day in production (t) were estimated using indoor climate parameters for the previous day (t-1) and animal body mass, temperature set points, and daily outdoor temperature averages corresponding to t. Air velocity at pig lying area was approximately 0.15 m / s. An average of 40 Watts pig^{-1} was used for heat supply purposes during the first three weeks of a winter production cycle. Values were averaged for the 90-day production cycle to provide context for the environmental and economic impact assessments.

To account for the operation of the production system under the different seasons of the year, daily outdoor temperature averages for the period 1971 to 2019 were collected from the nearest meteorological station at Sturup, Sweden (55.5231° N, 13.3787° E) (SMHI, 2020). As expected, winter was reported as the coolest season of the year with a mean of 0.42 ℃ (± 4.08 ℃), followed by spring (6.49 ℃, ± 4.96 ℃), autumn (8.63 ℃, ± 4.51 ℃) and summer (16.0 ℃, ± 2.82 ℃). The effect of seasonal ambient temperature variations on indoor climate parameters, energy consumption for climate control and heat stress related parameters was simulated using the indoor climate model described above. Potential direct and indirect effects on methane, ammonia, nitrous oxide and dinitrogen monoxide emissions were also modelled using temperature-specific variations factors for methane and ammonia emissions from literature (Rigolot et al., 2010; Pexas et al., 2020a)

4.2.3. Animal growth and manure management related emissions

Animals were reared from 30 kg to 115 kg (slaughter weight) in approximately 90 days. During this weight range a total of 238 kg of feed was consumed by each animal. Two cereal-based diet formulations were used in the production cycle: a ‘growing’ diet from 30 kg to 65 kg and a ‘finishing’ diet from 65 kg to 115 kg. Using specific feed conversion ratio for fattening pigs as reported by SLU, it was estimated that 97.8 kg of ‘growing’ feed was allocated during the first weight interval, and 140.2 kg of ‘finishing’ feed during the second one. Due to data limitations on water consumption, a 2:1 water-to-feed ratio was assumed according to the guidelines for welfare of pigs (DEFRA, 2020).

Methane (CH_4) emissions and nutrient excretion (N, P, K) associated with animal growth and the feed nutrient composition were estimated by tracking nutrient flows through the system components according to the mass balance principle. Following the same approach, CH_4, NH_3, NO_x, N_2 and N_2O emissions from slurry were modelled at pig housing (pen and slurry pits), slurry storage and field application. The IPCC guidelines were used for nutrient rates and methane emission factors (Dong et al., 2006). Emission factors for nitrogen and phosphorus related emissions were derived from relevant literature (Sommer et al., 2006; Botermans, et al., 2010; Pexas et al., 2020a).

4.2.4. Heat stress

The upper critical temperature was estimated for the average animal in the production cycle weighing approximately 72.5 kg, according to the method of Wellock et al., (2003). In addition to animal body mass and indoor temperature for the calculations, the study accounted for energy intake from feed, indoor relative humidity, voluntary pigskin wetting (~15%) and air velocity at pig lying area (~0.15 m/s). If the predicted indoor temperature remained above the estimated higher critical temperature for more than three consecutive days, indoor conditions were characterised as ‘hot’. When ‘hot’ conditions were identified, a heat stress effect on animal performance was simulated, applying a 17.2 % reduction in daily feed intake and a 38.7% reduction in average daily gain (Myer & Bucklin, 2001). Indirect heat stress effects on nutrient excretion, manure composition and related emissions at pig housing, manure storage and field application were modelled according to the mass balance approach.

Table 4.1 summarises the main variables used by the indoor climate control model and the model used to estimate the effect of heat stress on animal performance. Modelling of indoor climate, animal growth and heat stress related parameters was performed in R Studio v1.1.383 (R Core Team, 2020).

Table 4.1.: Key variables describing the production cycle under thermo-neutral conditions. Data sources: Swedish Board of Agriculture (2018); Jeppsson & Olsson (2020, February).

Variable (unit)	**Value**
Animal	
Body weight (kg)	30.0 – 115
Daily feed intake (kg)	1.30 – 2.70
Pig barn characteristics	
Surface area of building oriented on the outside (m^2)	2800
Mean thermal transmission coefficient, U ($W\ m^{-2}\ K^{-1}$)	0.500
Indoor climate	
Temperature set points, T_c (°C)	16.5 – 19.4
Minimum – Maximum ventilation rate ($m^3\ h^{-1}$)	8.50 – 95
Temperature bandwidth of control unit (°C)	4.00
Air velocity at pig lying area (m / s)	0.15
Heating required per animal, ~3 weeks during winter season (W)	40

4.2.5. Scenario analysis

The study evaluated the annualised potential environmental and economic impacts associated with the operation of the pig-fattening unit under non-cooling conditions and with the implementation of two pig-cooling strategies that aim to reduce ammonia (NH_3) emissions at pig housing and improve pen hygiene, through a decrease in pen fouling. The scenarios were developed using real data on the performance of the specific pig-cooling strategies, implemented in the system under consideration during the 2017-2019 period. Data were provided by experts in Swedish pig farming (Jeppson & Olsson, 2020 February, personal communication) (Table 4.2).

Pig cooling with showers

Showering over the slatted area of the pen was set to start whenever indoor temperature (T_i) exceeded the trigger point $T_{trig.shower} = T_c + 0.5$ °C, where T_c the variable temperature set point (Table 4.1). Shower duration increased linearly, starting from 1’ every 45’ for $T_i = T_c + 0.5$ °C, to a showering maximum of 2’ every 20’ for $T_i = T_c + 3$ °C. One flat nozzle per pen sprayed water at a 0.5 litre per minute capacity (Fig. 4.1). Normal operating hours for the shower cooling system were between 9:00 h and 20:00 h, plus any time outside of this range (i.e. during night) when the outdoor temperature was higher than 19 °C. With this cooling strategy the percentage of pig wet skin increased from ~15% to >50% and therefore, evaporative cooling of the animals increased. The average operating time observed for this cooling strategy was 44’ during a production cycle that occurred in winter (December, January, February), 2420’ during spring (March, April, May), 6790’ during summer (June, July, August) and 4232’ during autumn (September, October, November). Under these cooling conditions, ammonia emissions at pig housing reduced by 18% during spring, 54% during summer and 35% during autumn. No significant reductions were observed during winter.

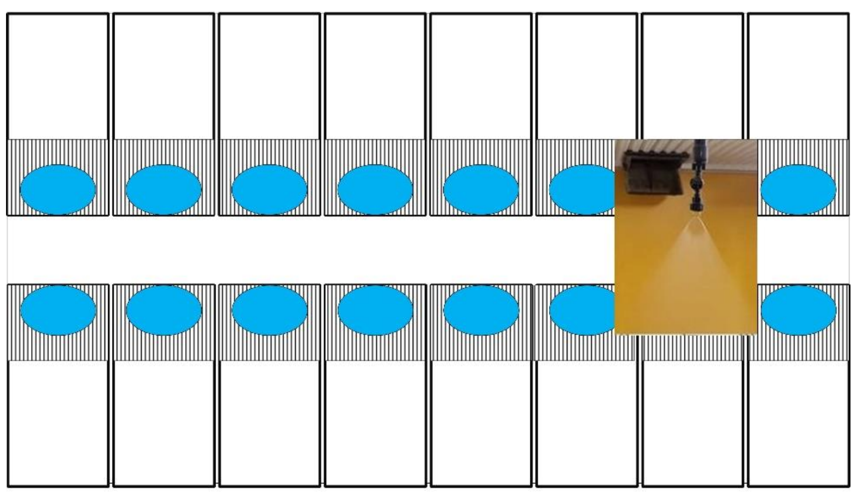


Figure 4.1.: Schematic representation of the ‘shower’ cooling system. One flat nozzle per pen sprays over the slatted (dunging) area of the pen, as illustrated by the elliptical shapes.

Pig cooling with increased air velocity at pig lying area

Convective cooling with increased air velocity at pig lying area was achieved by adjusting the angle of the air inlets in the barn from 75% open to 100% open (Fig. 4.2). Air velocity was increased at pig lying area from 0.15 m / s under non-cooling, to approximately 1 m / s. The increased air velocity cooling strategy was triggered when the incoming air was higher than a threshold temperature, which decreased from 27 °C for the first week of production to 17 °C after the 7th week of production in increments of approximately 1 °C per week. The operating time observed for the 'increased air velocity' strategy was 0' during winter, 13620' during spring, 53280' during summer and 7890' during autumn (total of 74790 minutes per year). This cooling strategy achieved 9% reductions in ammonia emissions at pig housing during spring, 21% during summer and 5% during autumn.

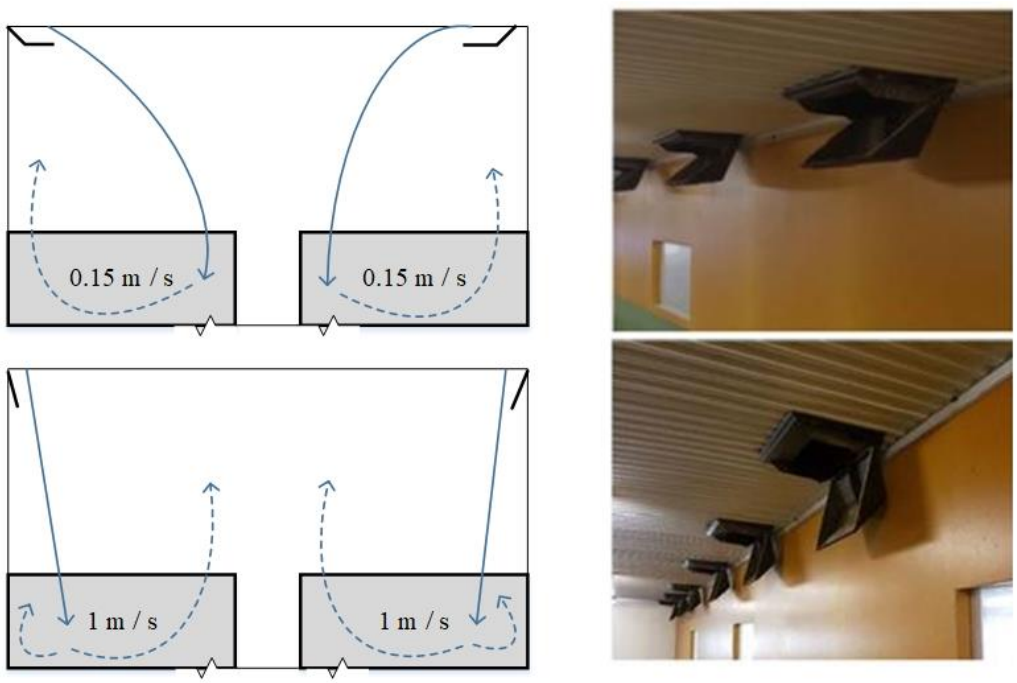


Figure 4.2.: Schematic description of the operation of the 'increased air velocity at pig lying area' pig-cooling strategy. The top figure illustrates air distribution with a maximum 75% air inlet opening, while the bottom figure illustrates air distribution with fully open (100%) air inlets. Irregular lines depict the slatted, excretory area of the pen.

Table 4.2: Key parameters that describe the implementation of the pig cooling with showers and pig cooling with increased air velocity scenarios. Data sources: Jeppsson & Olsson (2020, February).

Variable (unit)	**Value**
Pig cooling with showers	

No-cooling pig wet skin (%)	15.0
Cooling pig wet skin (%)	>50.0
Cooling strategy operating time during autumn (minutes)	4,232
Cooling strategy operating time during winter (minutes)	44.0
Cooling strategy operating time during spring (minutes)	2,420
Cooling strategy operating time during summer (minutes)	6,790
Ammonia emission reductions achieved during autumn (%)	35.0
Ammonia emission reductions achieved during winter (%)	0.00
Ammonia emission reductions achieved during spring (%)	18.0
Ammonia emission reductions achieved during summer (%)	54.0
Pig cooling with increased air velocity	
No-cooling air inlet opening (%)	75.0
Air inlet opening with cooling implemented (%)	100.
No-cooling air velocity at pig lying area (m/s)	0.15
Air velocity at pig lying area with cooling implemented (m/s)	1.00
Cooling strategy operating time during autumn (minutes)	7,890
Cooling strategy operating time during winter (minutes)	0.00
Cooling strategy operating time during spring (minutes)	13,620
Cooling strategy operating time during summer (minutes)	53,280
Ammonia emission reductions achieved during autumn (%)	5.00
Ammonia emission reductions achieved during winter (%)	0.00
Ammonia emission reductions achieved during spring (%)	9.00
Ammonia emission reductions achieved during summer (%)	21.0

4.2.6. Environmental life cycle assessment

A life cycle assessment framework was developed in SimaPro 8.5.0.0 (PRé Consultants, Amersfoort, The Netherlands) according to Pexas et al., (2020a). The goal of the framework was to model and compare the operation of the Swedish pig-fattening unit described earlier, for the baseline ('non-cooling conditions') and with each of the pig-cooling strategies implemented. Within the whole-farm system boundaries (Fig.3) the following components were modelled: i) feed production (i.e. diet formulations used), ii) animal growth at pig barn (30kg to 115 kg), iii) manure management at pig barn, storage and field. Tables A4.1-A4.3 of the Appendix, present the average environmental impact of inputs and outputs associated with the three scenarios modelled in this study, and characterisation factors for emissions identified at pig housing and manure management. To model relevant processes within the system boundaries, databases provided along with the SimaPro software were used (PRé Consultants, Amersfoort, The Netherlands). Agri-footprint and Agribalyse v1.3 were primarily used to model the feed production component, and the Ecoinvent 3 database was mainly used for processes related to pig housing and manure management (Colomb et al., 2013; Vellinga et al., 2013; AGRIBALYSE, 2016; Wernet et al., 2016; Agri-footprint, 2017). System expansion was used to avoid co-product allocation. When this was not possible, economic allocation was used (Weidema & Schmidt, 2010; Mackenzie et al., 2017a). The environmental impact for production cycles that occurred during the four different seasons of the year was estimated. The functional unit (FU) of the analysis was the production of 1 kilogram of live weight pig at slaughter weight adjusted for mortality rates. The annualised environmental impact for the pig farm was calculated as the summation of the equally weighted environmental impacts for each production cycle. The environmental impacts assessed were chosen based on the FAO guidelines for the environmental impact assessment of pig supply chains (FAO, 2018a) and the FAO guidelines for water use in livestock production (FAO, 2018b). Specifically, the CML Baseline v3.05 calculation method was used to estimate Non-Renewable Resource Use (NRRU) expressed in grams of antimony (Sb) equivalents, Non-Renewable Energy Use (NREU) expressed in mega-joules (MJ), Global Warming Potential (GWP) expressed in tonnes of carbon dioxide (CO2) equivalents, Acidification Potential (AP) expressed in tonnes of sulphate (SO2-) equivalents and Eutrophication Potential (EP) expressed in tonnes of phosphate (PO43-) equivalents. System water footprint was estimated through the Water Use (AWARE v1.01) and Blue Water Scarcity Index (BWSI) methods expressed in cubic meters of water used (m3). Finally, the ReCiPe 2016 Midpoint v1.01 method was used to assess agricultural Land Use (LU), expressed in square meters of crop land converted (m2). Each environmental impact category was assessed individually; the study did not attempt to aggregate across categories.

A Monte Carlo (MC) method (one thousand parallel simulations for each scenario compared against the baseline) was used for the quantification of uncertainties related to data inputs and to distinguish between uncertainties specific to each scenario or shared between scenarios. Whenever uncertainty information was not available for a variable relevant to any of the scenarios, the variable was assumed to be normally distributed with a standard deviation equal to 10% of the mean (Groen et al., 2014). The same Monte Carlo simulations method was used to perform pairwise comparisons and assess significance of differences in environmental impact between any two scenarios considered. If a scenario exhibited different (lesser or greater) environmental impact than the baseline for more than 95% of iterations, the results were considered to be significantly different (Mackenzie et al., 2015; Pexas et al., 2020a).

4.2.7. Economic impact analysis

Differences in farm economic impact between non-cooling and cooling scenarios were evaluated through a discounted cash flow over a 25-year time horizon (Pexas et al., 2020b). All cost and revenue streams within the system boundaries defined by the environmental LCA, were identified and linked to the best available financial information. In this way, the modelling approach followed in this study is consistent with the Life Cycle Cost Analysis method, except that a zero end-of-life disposal value of capital equipment was assumed, due to lack of data (Norris, 2001; Hunkeler et al., 2008; Swarr et al., 2011).

For the purposes of this analysis, a comprehensive list of economic data was compiled to describe all relevant processes (Table 4.3). Input and output prices were normalised whenever possible, using mean values over the 2012 – 2019 period, to smooth inter-year variability. Differences in specific costs and revenues for production cycles occurring in different seasons were included in the model.

Capital costs were calculated and amortised over a 25-year lifetime for building related components and a 12.5-year lifetime for technological equipment. Technological reinvestments were considered for equipment that was expected to be renewed at intervals more frequent than the time horizon. Costs related to the pig housing (i.e. building infrastructure, climate control, feed & water delivery and slurry removal technological equipment) and manure management component i.e. slurry storage and field application equipment) were considered. Working capital comprised the purchasing of piglets at 30 kg and direct veterinary/medical inputs.

Operational expenses included animal, pig housing management and manure management related costs such as feed, electricity and diesel fuel, technological equipment maintenance and labour. Annual maintenance costs for the building and technological equipment including the pig showering system were estimated as 2.50% of the relevant capital costs. Because no capital investment was required for the implementation of the increased air velocity strategy, a 50% increase in maintenance of the ventilation system was considered to maintain good air distribution and operation of this strategy (Pexas et al., 2020b).

Total revenues consisted of live weight pig meat sold and avoided costs of synthetic fertiliser at crop production replaced by the field application of manure.

To evaluate investment feasibility the study estimated two farm financial metrics commonly used to compare the economic performance of alternative investments; the whole-farm Annual Equivalent Value (AEV) and the whole-farm Internal Rate of Return (IRR). To estimate these it was necessary to first calculate the whole-farm Net Present Value (NPV) (Eq.4.1). AEV is a measure of the annualised monetary return of an investment (Eq.4.2) and can be used as a proxy to estimate the annual profitability of the farm as a whole. IRR represents an investment's expected percentage return on capital over the time horizon.

$$(\mathbf{Eq. 4.1})\ NPV = \sum_{t=1}^{T} \frac{Rev_t - OpEx_t - RenC_t}{(1+d)^t} - ICI$$

$$(\mathbf{Eq. 4.2})\ AEV = \frac{d(NPV)}{1-(1+d)^t}$$

Where, d = discount rate, T = total number of years in time horizon, t = each individual year, *Rev* = revenues, *OpEx* = operating expenses, *RenC* = renewal costs for technological equipment whenever its lifetime was less than the time horizon, and *ICI* = initial capital investment.

IRR is also estimated through Eq.4.1, by solving for the discount rate that satisfies the condition "*NPV = 0*".

Table 4.3.: Main costs associated with the operation of a typical pig-fattening unit in southern Sweden that produces slaughter pigs to 115 kg.

Variable	Unit	Value	Data Sources
Main economic analysis assumptions			
Discount rate	%	7.00	Larsson (2020, February)
Building lifetime	years	25.0	Pexas et al. (2020b)
Technological equipment lifetime	years	12.5	> >

Costs			
Piglet at 30 kg	€ per pig	63.9	Larsson (2020, February)
Growing feed, complete formulation	€ per kg	0.427	Statistics Sweden (2019)
Finishing feed, complete formulation	€ per kg	0.260	> >
Water	€ per litre	Free of charge	
Labour, trained farm worker	€ per hour	22.3	Statistics Sweden (2018c)
Veterinary / medicine	€ per pig	0.950	Statistics Sweden (2019)
Electricity, household, grid-mix	€ per kWh	0.168	Statistics Sweden (2018b)
Diesel fuel	€ per litre	1.14	Statistics Sweden (2019)
Cost of installation for technological equipment (incl. labour, machinery, consumables)	% capital cost	20.0	Adapted from Pexas et al. (2020b); Jeppsson & Olsson (2020, February)
Annual maintenance of buildings and technological equipment	% capital cost	2.50	> >
Flat nozzle shower cooling system, purchasing	€ per pen	21.0	Statistics Sweden (2019)
Insurance (building, technological equipment)	% capital cost	0.250	Pexas et al. (2020b)
Revenues			
Pig meat sold	€ per kg live weight	1.61	Statistics Sweden (2019)
Urea fertiliser	€ per kg	0.314	Adapted from FAO (2019)
Di ammonium phosphate fertiliser	€ per kg	0.460	> >
Potassium chloride fertiliser	€ per kg	0.339	> >

The cost of abatement for each individual environmental impact category associated with each pig cooling strategy was then estimated. This was calculated through the following equation (Eq. 4.4):

$$(\mathbf{Eq. 4.3})\ €\ per\ unit\ of\ pollutant\ abated = \frac{\Delta AEV}{\Delta EI} \times -1$$

Where, ΔAEV = difference in AEV between a cooling and the baseline, no-cooling scenario, and ΔEI = difference in environmental impact between cooling and no-cooling scenarios.

Figure 4.3 below summarises the main components identified within the system boundaries of the pig farming system assessed, and graphically describes the methodological flow followed to evaluate whole-farm environmental and economic consequences under 'no-cooling', 'cooling with showers' and 'cooling with increased air velocity' scenarios.

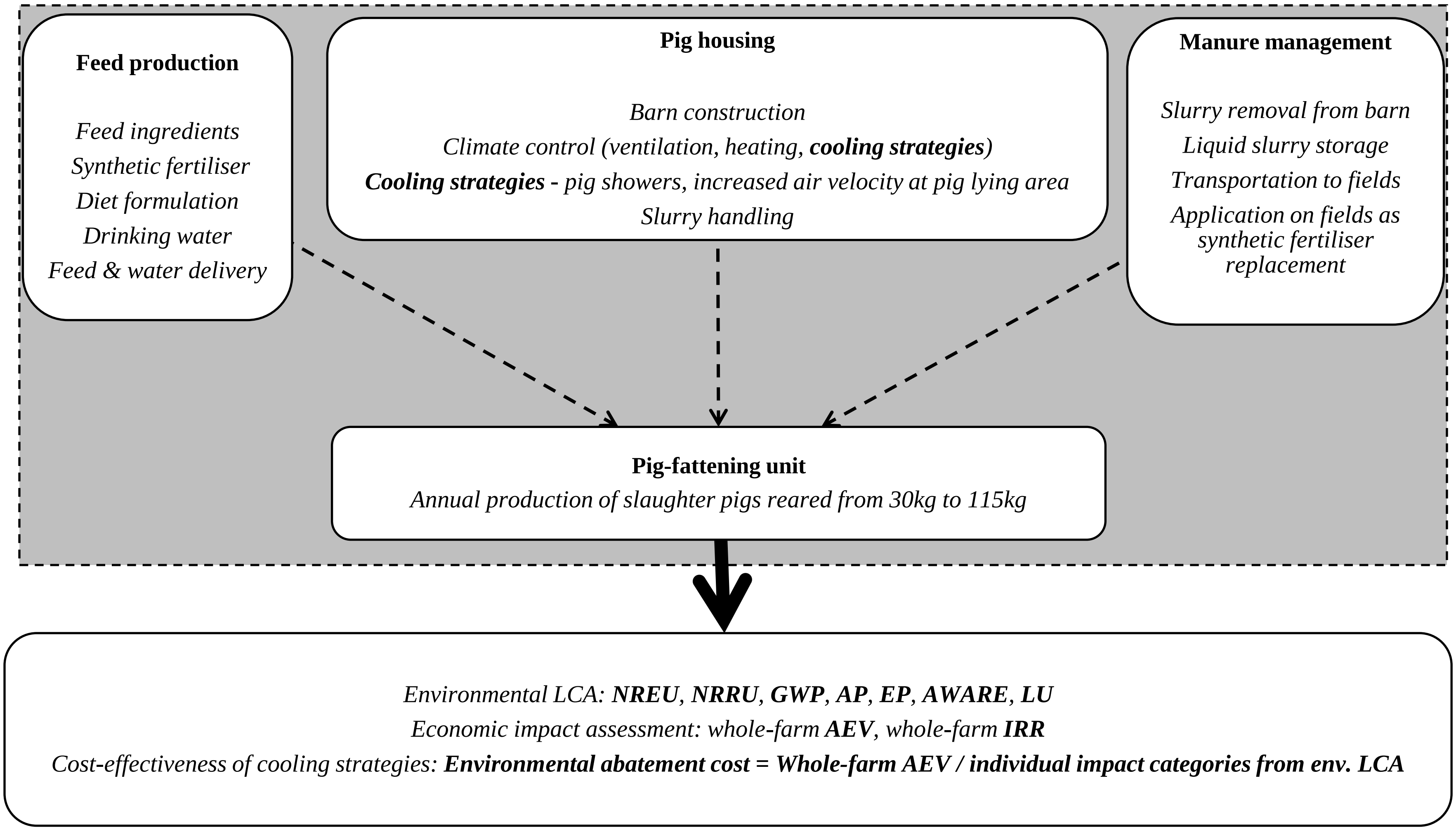


Figure 4.3: Schematic representation of the main components identified within the system boundaries of the analysis. The grey shaded area represents the life cycle inventory description phase (system description), which was the basis for the development of the integrated, life cycle based cost-effectiveness framework. LCA = Life cycle assessment, AEV = Annual equivalent value, IRR = Internal rate of return, NREU = Non-renewable energy use, NRRU = Non-renewable resource use, GWP = Global warming potential, AP = Acidification potential, EP = Eutrophication potential, AWARE = Available water resources, LU = Land use.

4.2.8. Integration of the environmental-economic models with projected climate data

A sensitivity analysis was carried out to investigate the implications of projected ambient temperature increases for Sweden caused by climate change on the relative cost-effectiveness of the environmental impact mitigation provided by pig-cooling scenarios. The effect of increasing ambient temperature on the system environmental and economic impact was evaluated for the three different scenarios considered. Specifically, ambient temperature was incrementally increased to simulate the effect of climate change on the environmental and economic performance of the production cycle during the warmest season of the year. Five increments of +0.52 °C were used to simulate a total +2.6 °C average temperature increase as projected by the Representative Concentration Pathway (RCP) 4.5 scenario (IPCC, 2014). A Monte Carlo method (1000 iterations) was used to simulate the model for each step of the sensitivity analysis. Significance of difference between scenarios for the different cooling conditions was evaluate using the pairwise Monte Carlo comparisons method described in the previous sections.

4.3. Results and Discussion

The chapter first presents the outcomes of the indoor climate and heat stress models that provided context for the environmental and economic impact analyses. It then presents the environmental life cycle assessment and the whole-farm financial performance of the Swedish pig-fattening unit under 'non-cooling' conditions and the two cooling scenarios considered. The results of the integration of the framework with projected climate data to investigate the effect of ambient temperature increase on system environmental and economic performance are presented last.

4.3.1. Indoor climate and heat stress

Indoor climate and heat stress relevant parameters were estimated for the average animal of the pig-fattening unit, weighing approximately 72.5 kg on the 45th day of the production cycle. Sensible heat production from the average pig was estimated at ≅289 W. The specific indoor temperature and ventilation rate estimates followed seasonal variations of outdoor temperature. The warmest period of the year was during the summer production cycle with average indoor temperatures of approximately 23.0 °C. Under such conditions, the ventilation system operated at a maximum capacity providing approximately 95 m^3 / h per animal. The average indoor temperature for the autumn production cycle was estimated at ~18.5 °C, and at ~18.0 °C and ~16.5

°C for spring and winter respectively. Average ventilation rates were estimated at approximately 30.1 m^3 / h, 19.3 m^3 / h and 8.50 m^3 / h per animal for autumn, spring and winter respectively. Average sensible heat losses due to transmission through the building were ≅5880 W during a summer production cycle, ≅6180 W during autumn, ≅7200 W during spring and ≅10100 W during winter.

An upper critical temperature was estimated for the average pig at approximately 26.8 °C, beyond which the effects of heat stress on animal performance become noticeable. According to the indoor climate and heat stress models, 'hot' conditions were observed only for approximately 10.0 % of the duration of a summer production cycle and resulted in a 3.50 kg reduction in feed intake and a 4.00 kg reduction in slaughter weight for the specific production cycle. Upper critical temperature increased with the implementation of both pig-cooling strategies. Pig-cooling with showers allowed the animals to wet more than 50% of their skin increasing evaporative cooling and therefore, increased the perceived upper critical temperature from 26.8 °C to higher than 32.2 °C. When pig-cooling with increased air velocity (1 m/s) at pig lying area was simulated, estimated upper critical temperature was raised at 31.5 °C. Both pig-cooling scenarios completely removed the effects of heat stress on growth rate and feed intake, since indoor temperature never exceeded the upper critical temperature thresholds for prolonged periods in the south Swedish pig-fattening unit and therefore, animals did not experience 'hot' conditions.

Similarities in climatic conditions between southern Sweden and Central European countries, provide a potential explanation for agreement of specific results with past studies that used temperature-humidity indices to estimate heat stress thresholds in different European pig-fattening units (Vitt et al., 2017; Mikovits et al., 2019). Diet composition and growth rate specific to different management systems play an important role in the estimation of heat stress parameters. Herd and pig housing management choices such as stocking density or the provision of bedding in the pen can also affect estimates for critical temperature thresholds. While in this study indoor climate and heat stress parameters were compared for scenarios that referred to one specific pig-fattening unit, variations in such factors should be considered to ensure reliability when performing 'between – pig farm' comparisons (Wellock et al., 2003).

4.3.2. Environmental impact assessment

Table 4.4 summarises the system environmental performance over the different impact categories for the three cooling scenarios considered. Differences between scenarios are presented at a 95% significance level. When pig-cooling with showers was implemented, the largest reduction of -3.28% was observed for acidification potential. Non-renewable resource use and eutrophication potential were also significantly reduced by -1.14% and -0.960% respectively. Smaller but also significant reductions were observed for global warming potential (-0.508%), non-renewable energy use (-0.500%), and agricultural land use (-0.395%). The water footprint assessment did not reveal any significant differences for either blue water scarcity or water use when pig-cooling with showers was compared to the non-cooling baseline.

Increased air velocity achieved its largest abatement potential also for acidification potential (-1.51%). Significant reductions were observed for non-renewable resource use (-0.789%) and non-renewable energy use (-0.636%) too. Smaller, but significant reductions were achieved for eutrophication potential (-0.564%), global warming potential (-0.606%), and agricultural land use (-0.229%). Water footprint was not significantly different when implementing the increased air velocity strategy either.

Comparisons between the environmental performances of the two pig-cooling strategies revealed significant differences only for acidification potential, eutrophication potential and non-renewable resource use. More specifically, pig-cooling with showers significantly outperformed the increased air velocity strategy, achieving 1.76%, 0.396% and 0.349% larger abatement potential for acidification, eutrophication and non-renewable resource use respectively. For all other impact categories assessed, the two pig-cooling strategies exhibited approximately the same performance.

Table 4.4.: Annualised (three production cycles) environmental impact of the pig-fattening unit under non-cooling conditions (baseline) and with the implementation of pig-cooling with showers and pig-cooling with increased air velocity (1000 Monte Carlo simulations). Significance of difference between pig-cooling with showers and pig-cooling with increased air velocity (1000 Monte Carlo simulation pairwise comparisons) is indicated by asterisk (*) and alpha (a) if impact of showers was smaller than increased air velocity or beta (b) for the opposite case. Non-significant between pig-cooling with showers and pig-cooling with increased air velocity are indicated by "n.s" superscript (significance level = 95%).

Environmental Impact		**Non-cooling (baseline)**	**Showers**	**Increased air velocity**
Non-renewable resource use (g Sb eq.)	Mean	499.	494.*[a]	495.

	% ≤ baseline		100	100
Non-renewable energy use (GJ)	Mean	3,874	3,854$^{n.s}$	3,849
	% ≤ baseline		100	100
Global warming potential (ton CO_2 eq.)	Mean	971.	966.$^{n.s}$	965.
	% ≤ baseline		100	100
Acidification potential (ton SO_2^- eq.)	Mean	8.74	8.45*^{a}	8.61
	% ≤ baseline		100	100
Eutrophication potential (ton PO_4^{3-} eq.)	Mean	10.0	9.94*^{a}	9.98
	% ≤ baseline		100	100
Land use (km^2)	Mean	1.31	1.31$^{n.s}$	1.31
	% ≤ baseline		100	100
Water use (m^3)	Mean	43,514	43,306$^{n.s}$	42,972
	% ≤ baseline		32.0	30.7
Blue water scarcity index (m^3)	Mean	1,860	1,853$^{n.s}$	1,841
	% ≤ baseline		29.3	28.7

Several factors can explain the observed differences in system environmental impact under the different cooling scenarios. When indoor temperature is relatively high, pigs change their lying and dunging behaviour, and exhibit fouling on the solid area of the pen. As a result, the larger slurry surface that is exposed to air allows for increased ammonia volatilisation and emissions at pig housing (Aarnink et al., 2006). Ammonia emissions largely contribute to acidification potential, eutrophication potential and even global warming potential (Dong et al., 2006; De Vries & De Boer, 2010). The use of frequent showers and increased air velocity at pig lying area during 'hot' conditions can help prevent animals from excreting on the lying, solid area or lying on the excretory area of the pen, and therefore improve the system environmental performance through reduced ammonia emissions (Botermans et al., 2010). Reductions in system environmental impact when implementing pig-cooling with showers could also be explained by the large potential for mitigation of ammonia emissions achieved when slurry is diluted and the concentration of ammoniacal nitrogen reduced (Rigolot et al., 2010; Pexas et al., 2020a).

Variations in slaughter weight from impaired animal performance critically affect environmental impact allocation over the functional unit in the life cycle assessment framework and could also explain the observed differences in environmental performance. Under no-cooling conditions, heat stress resulted in delivery of lighter pigs during the summer production cycle and reduced feed intake. Increasing air velocity at pig lying area from 0.15 m/s (non-cooling baseline) to 1 m/s, or implementing frequent pig showers to increase evaporative cooling from pig wet skin, resulted to mitigation of the effect of 'hot' conditions on animal growth rate and feed intake, which resulted in the improved system environmental performance. On the other hand, because feed production is among the largest contributors in environmental impact arising from pig production (FAO, 2018a) the increased feed intake under cooling conditions might have acted against the maximum abatement potential associated with the operation of either cooling strategy. Increased feed intake could explain the better environmental performance for non-renewable resource use with the implementation of increased air velocity and pig showers. More feed consumed resulted in higher concentrations of nutrients available in manure to replace synthetic fertiliser for crop production, a main contributor to this impact category (Pexas et al., 2020a).

The system water footprint did not significantly change with the implementation of pig-cooling with showers. While the production of water and electricity for on-farm use contributes to both the water use and blue water scarcity index impact categories, the additional requirements for the operation of the showering system were not large enough to significantly increase the system water footprint. High uncertainties associated with specific data and methods used for the water footprint assessment could explain the observed inconsistencies.

Although the environmental abatement potential of the pig cooling methods tested here is small relative to other potential farm interventions (Pexas et al., 2020a), it is important to emphasize that the implementation of cooling strategies may have implications also on animal health and welfare, and by extension to the input of medication in pig systems (Silva et al., 2008). Although in this study no changes in the use of antimicrobials were observed, increased environmental temperature and humidity has been associated with increase in the incidence of respiratory conditions and vice, such as tail biting (Velarde & Dalmau, 2012; Scollo, Contiero & Gottardo, 2016; Jukan, Masip-Bruin & Amla, 2017). The study suggests that in future research and prior to the implementation of such strategies, considerations of potential effects on animal health and welfare are taken into account.

4.3.3. Economic impact assessment

Table 4.5 summarises the major financial performance metrics estimated for the 'non-cooling' baseline and the two pig-cooling scenarios. Under non-cooling conditions the whole-farm annual equivalent value was equal to € 52,961 and the internal rate of return equal to 16.4%. The discounted cash flow analysis showed that the implementation of the pig-cooling with showers strategy was the most profitable system configuration overall. More specifically, whole-farm annual equivalent value with this pig-cooling strategy was € 56,558 (+6.79% compared to 'non-cooling conditions') and its internal rate of return 17.0%. Pig-cooling with increased air velocity was less profitable, with whole-farm annual equivalent value estimated at € 54,747 (+3.37% compared to 'non-cooling conditions') and internal rate of return at 16.8%. In terms of cost of production per kg of live weight pig meat, the costliest scenario was the non-cooling baseline at € 1.36. When pig-cooling with increased air velocity was implemented, cost of production per kg of pig meat produced reduced by -1.02% (€ 0.0139). Pig-cooling with showers reduced this further, by -1.10% (€ 0.0150) compared to the non-cooling baseline.

The main sources for the observed differences in farm profitability between the cooling scenarios can be identified by breaking down the cost and revenue streams. Increased air velocity required a +0.451% increase in cash overheads from additional annual maintenance of the housing component. With the mitigation of heat stress effects on feed intake and animal growth rate, feed related costs increased by +0.904% (€ 2,776), and revenues from pig meat sold and manure application by +0.664% (€ 4,824), when compared to the non-cooling baseline. Specifically, urea fertiliser discounts increased by +0.904% (€ 15.5), di-ammonium phosphate by +0.954% (€ 16.4) and potassium chloride by +0.586% (€ 10.1). Consequently, budgeted cash margins increased by +0.267% (€ 1,938) with this strategy. Relatively high additional capital and operating costs were associated with the implementation of the shower cooling strategy. When compared to the non-cooling scenario, pig-cooling with showers required a +0.378% (€ 2,749) higher investment in capital costs at year 0, +0.378% (€ 2,749) higher costs associated with the renewal of technological equipment at year 12.5 and +0.904% (€ 2,776) feed related costs. However, revenues from pig meat sold increased by +0.664% (€ 4,824), urea fertiliser discounts increased by +1.08% (€ 18.7), while di-ammonium phosphate and potassium chloride discounts were identical to the ones achieved with the implementation of increased air velocity. Therefore, whole-farm budgeted cash margins were +0.584% (€ 4,246) higher compared to the non-cooling baseline.

On-farm water consumption is free-of-charge in Sweden and so the variable costs associated with the operation of pig-cooling with showers could be higher if the system was implemented in a different country, further reducing farm profitability. For example, if water prices were included instead (e.g. € 0.00840 per litre as is the case in neighbouring Denmark) the observed difference in whole-farm AEV between the pig showers strategy and 'non-cooling conditions' would be smaller, at +3.81% (€ 2,016).

Potential economic impacts associated with the implementation of animal cooling strategies, may finally be identified in relation to their implications for animal health and the reductions they can cause in welfare. Reducing costs for medication and treatments required on such occasions, can further improve farm economic performance (Velarde & Dalmau, 2012; Sneeringer, MacDonald, Key, McBride & Mathews, 2015).

Table 4.5.: Financial performance metrics are presented for the operation of the pig-fattening unit under 'non-cooling conditions' and with the implementation of each pig-cooling strategy, as evaluated over the 25-year time horizon. The cost-effectiveness of each pig-cooling strategy is presented as the cost of abatement they exhibited for environmental impacts they significantly mitigated. A negative cost indicates that profit was generated along with the mitigation of the specific impact category.

	Unit	**Non-cooling**	**Showers**	**Increased air velocity**
Financial performance				
Whole-farm Annual Equivalent Value	€	52,961	56,558	54,747
Whole-farm Net Present Value	€	670,149	715,663	692,740
Whole-farm Internal Rate of Return	%	16.4	17.0	16.8
Cost of production	€ / kg pig live weigh	1.36	1.35	1.35
Cost of abatement				
Non-renewable resource use	€ / g Sb eq. abated	N.A	-8.36 E-04	-7.54 E-04
Non-renewable energy use	(€ / GJ abated)	N.A	-2.85 E-03	-4.71 E-03
Global warming potential	(€ / ton CO_2 eq. abated)	N.A	-7.25 E-04	-1.12 E-03
Acidification potential	(€ / ton SO_2^- eq. abated)	N.A	-4.21 E-05	-2.53 E-05
Eutrophication potential	(€ / ton PO_4^{3-} eq. abated)	N.A	-1.42 E-05	-1.08 E-05
Land use	(€ / km^2 abated)	N.A	-7.64 E-07	-1.45 E-06

4.3.4. Environmental and economic trade-offs assessment

Although both investments were cost-effective in mitigating the system environmental impact for most impact categories considered, important trade-offs were identified. Pig-cooling with showers was the more cost-effective scenario for non-renewable resource use, acidification and eutrophication potential generating €8.36 E-04 of profit per g Sb eq., €4.21 E-05 per ton SO_2^- eq., €1.42 E-05 per ton PO_4^{3-} eq. mitigated respectively. For the same impact categories, increased air velocity generated €7.54 E-04 of profit per g Sb eq., €2.53 E-05 per ton SO_2^- eq., €1.08 E-05 per ton PO_4^{3-} eq. mitigated. An opposite trend was observed for mitigation of non-renewable energy use, global warming potential and land use, where increased air velocity was more cost-effective option. More specifically, it generated €4.71 E-03 of profit per GJ, €1.12 E-04 per CO_2 eq. and €1.45 E-06 per km^2 mitigated, while pig-cooling with showers generated smaller profits of €2.85 E-03 per GJ for non-renewable energy use, €7.25 E-04 per CO_2 eq. for global warming potential and €7.64 E-07 per km^2 for land use mitigation. Further analysis on the potential synergies between the two pig-cooling strategies, could provide alternative options through combinations that prioritize on specific objectives (i.e mitigation of acidification potential).

4.3.5. Sensitivity analysis for climate change consequences on system environmental impact

Figures 4.4a-4.4f present the effect of ambient temperature increase on system environmental impact, for categories that were significantly affected in one or more of the cooling scenarios considered.

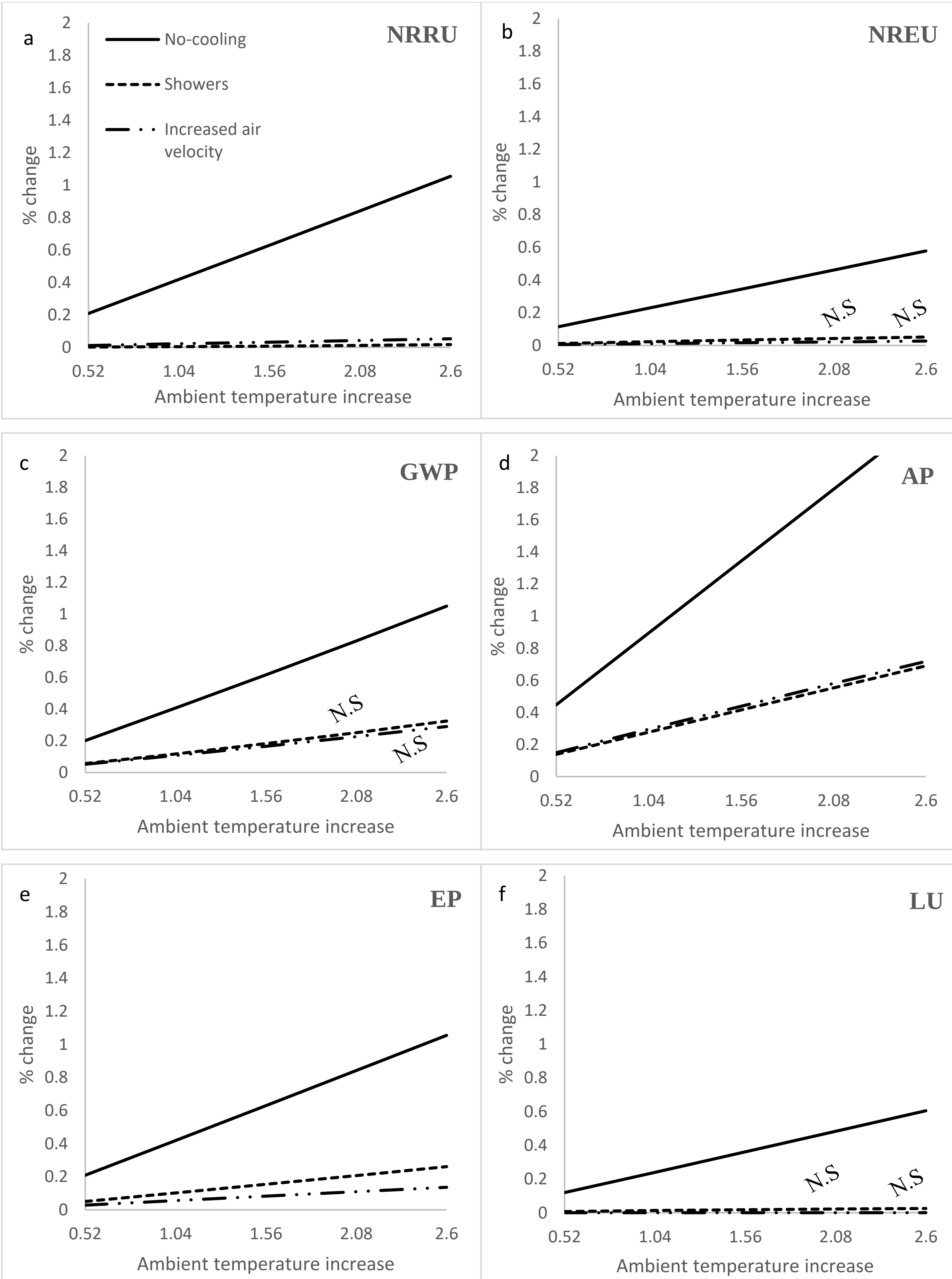
When ambient temperature was increased under non-cooling conditions, system environmental impact increased significantly in a linear way for all categories except water footprint (water use and blue water scarcity index). For a +2.6 ℃ increase in ambient temperature, acidification potential was +2.24% significantly higher compared to the baseline climate conditions. Significant increases were observed also for non-renewable resource use (+1.05%), global warming potential (+1.05%) and eutrophication potential (1.05%). Land use was affected less but also significantly, exhibiting a +0.605% increase.

Both pig-cooling strategies greatly mitigated these effects and significant changes were only observed for non-renewable resource use, acidification potential and eutrophication potential. Specifically, when the performance of increased air velocity strategy was tested under increasing ambient temperature conditions, a significant increase of +0.718% was observed for acidification, +0.136% for eutrophication potential, and +0.0526% for non-renewable resource use. Pig-cooling with showers was more robust and exhibited even smaller but still significant increases of +0.690% for acidification, +0.261% for eutrophication potential, and +0.0171% for non-renewable resource use.

The direct effect of temperature on ammonia and methane emissions at pig housing could provide an explanation for the observed significant effects of ambient temperature increase on system environmental impact (Rigolot et al., 2010; Pexas et al., 2020a). Ammonia emissions are among the largest contributors to acidification potential associated with pig production and therefore, we expected that the main effect would be observed for this impact category. These findings highlight the importance of such strategies for the mitigation of system environmental impact under the threat of climate change and increasing temperatures.

As anticipated, the amount of days perceived as ‘hot’ during the warmest season also increased linearly with ambient temperature. Intense confined livestock systems are particularly sensitive to prolonged ‘hot’ climatic conditions due to the inability of ventilation system alone to maintain indoor temperatures low for animals and the effects of heat stress on animal performance are amplified in such environments. Further reduction of slaughter weight could explain the observed increases in system environmental impact across all impact categories, and that cooling strategies, which mitigate heat stress, were more resilient to ambient temperature increase than the non-cooling baseline. When ambient temperature increased by +2.6 ℃ under non-cooling conditions, slaughter weight reduced to 109 kg. The ‘wind-chill’ effect achieved by the increasing the air velocity at pig lying area and the increased evaporative cooling caused by the pig showers, increased the perceived upper critical temperature at ~31.5 ℃ and ~32.2 ℃ respectively. Therefore, with the implementation of either strategy in the temperature range tested, the animals did not experience any heat stress related effects on growth rate and feed intake.

No significant effects were observed for either of the water footprint impact categories. Water use, feed production and electricity consumption would be the main contributors to system water footprint. Reductions in feed intake caused by the prolonged heat stress did not result to consistent differences in system water footprint, which might be attributed to data and method related uncertainties for the specific impact categories. Changes in electricity consumption for indoor climate control were negligible and did not cause a significant effect on model outcome for water use and blue water scarcity.



a
NRRU
No-cooling
Showers
Increased air velocity
% change
Ambient temperature increase
b
NREU
N.S
N.S
c
GWP
N.S
N.S
d
AP
e
EP
f
LU
N.S
N.S
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0.52
1.04
1.56
2.08
2.6

Figure 4.4a-4.4f: The effect of ambient temperature increase on system environmental impact for categories that were significantly affected under one or more cooling scenarios (>95% of Monte Carlo simulations). The y-axis presents the percentage change in environmental impact compared to a baseline where ambient temperature represents current climate conditions. NRRU = Non-renewable resource use, NREU = Non-renewable energy use, GWP = Global warming potential, AP = Acidification potential, EP = Eutrophication potential, LU = Land use. N.S = non-significant difference

Increasing ambient temperature affected farm profitability mainly in relation to revenues from sold pig meat. Due to slaughter weight reductions, when temperature increased by +2.6 ℃, pig meat revenues reduced by -0.441% (€ 3,188) under non-cooling conditions. As expected, the magnified heat stress effects also affected annual feed related costs, which reduced by -0.208% (€ 638). In terms of whole-farm annual equivalent value, the increased ambient temperature resulted to a -4.43% decrease under non-cooling conditions. The specific farm costs and revenues were unaffected when pig cooling with showers or increased air velocity were implemented.

While the main economic impact of increased ambient temperature was directly related to variability in the quantity of pig meat sold, other potential implications might arise such as batch uniformity penalties depending on policies specific to the slaughter plant, or additional costs relevant to potential increases in operating frequencies of the pig-cooling strategies. An elaboration of the analysis with the inclusion of such parameters, which were not captured in this study due to data limitations, would enhance the accuracy of predictions for the economic performance of such strategies under changing climate conditions.

4.3.6. Methodological implications and challenges in developing integrated environmental-economic models for animal housing investments

Through the more focused study described in this chapter, the potential for animal cooling strategies to improve farming system sustainability were presented. Furthermore, important trade-offs that policy makers have to face when comparing the cost-effectiveness of potential farm investments to identify sustainable solutions were highlighted. While Swedish slaughter pig production was used as a case-in-point, the methodological framework presented here can be applied to a range of technologies and strategies in pig production, but also on other livestock systems (e.g. broiler, dairy cow) and on a broader geographical scale (Pexas et al., 2020b). The specific results generated in this study also have wider implications for the European pig production sector. Potential environmental and economic benefits that arise from the implementation of the two cooling strategies become more relevant in warmer countries, and may even be amplified when implemented in less advanced systems in terms of climate control technologies involved at housing, where animals experience unstable climate and greater frequency of heat stress events (Valiño et al., 2010; Skuce, Morgan, Van Dijk & Mitchell, 2013).

The study acknowledges that cost and revenue streams within the various scenarios modelled are dynamic and particularly sensitive to geographic and temporal variability. In cases, as the one presented in this chapter, where many of the economic parameters are considered static, the discounting method remains useful in accounting for decision makers' time preferences when comparing the differing life-time cash flow profiles of alternative investments. For this reason, DCF has been a standard practice in environmental life cycle costing, despite challenges with issues such as the choice of discount rates to accurately represent both business transactions and environmental considerations, and occasional inconsistencies in product economic (or useful) versus actual lifetime (Hunkeler et al., 2008; Kloepffer, 2008; Swarr et al., 2011). Availability of information about spatiotemporal variations in prices of feed and water, relevant construction materials, and batch uniformity penalties would allow for the development of a stochastic financial assessment framework enhancing reliability of comparisons, particularly in 'between-farm' analysis designs. Availability of qualitative, economically relevant information about the stakeholders' preferences (e.g. farm manager investment behaviour) would also allow for better predictions of the cost-effectiveness of potential farm investments projected in the future (Mackenzie, Wallace & Kyriazakis, 2017). An important challenge was identified in dealing with uncertainties when combining environmental LCAs and economic modelling, due to limited availability of resources and the sheer extent of life cycle inventory describing the presented models. Further investigation is suggested for the implementation of methods such as the pedigree matrix to account for data related uncertainties within integrated LCAs (Ciroth, Muller, Weidema & Lesage, 2016). Such a methodological exercise requires exploration in its own right, and emphasis beyond what the resources allowed for in this study.

In the modelling framework presented in this chapter, the number of 'hot' days during the warmest season increased linearly with ambient temperature. However, this assumption of linearity may lead to underestimation of the potential economic and environmental benefits of the pig-cooling strategies investigated, as it does not account for climate variability. While mean air temperatures are consistently predicted to increase globally in the coming years by climate modellers (IPCC, 2014; Hausfather, Drake, Abbott & Schmidt, 2020), some also project increased variation from that mean in specific regions (Bathiany, Dakos, Scheffer & Lenton, 2018; Chen, Dai & Zhang, 2019). As predictions around temperature variability in climate projections is subject to debate among climate modellers (Huntingford, Jones, Livina, Lenton & Cox, 2013) the study did not address it in the sensitivity analysis. However, increased temperature variability could potentially increase the number of 'hot' days further as mean temperature rose, and lead to increased environmental and economic benefits arising from investments in pig cooling strategies. In the Swedish case study presented here, there was no need for pig cooling strategies to operate during the winter season. This situation may change if the expected winter temperature variability due to climate change materialises (Castro-Díez, Pozo-Vázquez, Rodrigo & Esteban-Parra, 2002).

While this study considered the two pig-cooling strategies as mutually exclusive, it acknowledges that potential synergistic effects could be achieved to further improve system environmental performance and, provided that relevant data exists, their combined implementation should be investigated as a potential abatement scenario. Also, a homogeneous air distribution was assumed for the simulations of this study, due to data limitations about the variability of wind speed at pig lying area. However, in order to achieve and maintain such homogeneity of air velocity throughout the pen in real conditions, novel ventilation systems should be implemented.

The development of accurate LCA models that address both the environmental and economic aspects of complex production systems in the agri-food sector is a data intensive process. Here the expectation was to obtain detailed data about the effects of cooling strategies on indoor climate (precise measurements of temperature and humidity across scenarios) and emissions at pig housing (ammonia levels on a high temporal resolution). Furthermore, the data collection process aimed to compile information about potential synergies of the two cooling strategies. However, data of such quality was not always available, which is why the study resorted to the specific assumptions described in this chapter. Future studies should focus on the generation of primary data to facilitate modelling of novel on-farm solutions for improved sustainability.

4.4. Conclusions

The implementation of pig-cooling strategies that target ammonia emission reductions at pig housing have important environmental and economic implications at a whole-farm level. Here, a novel environmental and economic impact assessment framework is presented and its potential to facilitate decision making regarding the implementation of such farm investments in a cost-effective manner is demonstrated. Through the presented framework, potential environmental (i.e. indoor temperature) and economic (i.e. feed and water price) impact hotspots can also be identified to help improve farm sustainability. The study concludes that both pig-cooling with showers and pig-cooling with increased air velocity can significantly reduce system environmental impact, while improving farm profitability. Both pig-cooling strategies were resilient and effective in significantly reducing the effects of climate change on system environmental impact for all impact categories. Notwithstanding the challenges in adopting whole-farm, life cycle assessment approaches, this study demonstrates the importance of using such elaborate models to evaluate potential environmental and economic impacts associated with farm investments that aim to improve the system environmental performance.

Chapter 5. Accounting for spatial variability in life cycle cost-effectiveness assessments of environmental impact abatement measures

Abstract

The environmental and economic impacts of livestock production systems are typically assessed using global characterisation factors and data, even though several impact categories call for site-specific assessments. In this study, spatial variability is accounted for by addressing potential interactions between geographic locality and the cost-effectiveness of farm investments that aim to reduce system environmental impact, using Danish pig production as a case-in-point.

An LCA based, spatially explicit environmental abatement cost framework was developed to assess the cost-effectiveness of potential environmental abatement strategies. The framework was tested for Danish pig production in a "4 manure management x 4 geographic location" scenario analysis design. In addition to the baseline, the alternative manure management strategies were on-farm anaerobic digestion, slurry acidification and screw press slurry separation, implemented in an integrated pig farming system. The geographic locations differed in their proximity to Natura 2000 areas and in pig farming density. Eight different impact categories were assessed through an LCA using spatially explicit characterisation factors whenever possible and annualised abatement potential was estimated for each manure management scenario and in each geographic location. The financial performance for each scenario was also estimated, through a discounted cash flow analysis at a whole-farm level.

Significant interactions were observed between geographic location and system environmental and economic performance under baseline conditions. Significant location effects were also observed for the cost-effectiveness of all manure management strategies tested. Anaerobic digestion was the only "win-win" strategy that increased farm profits while reducing system environmental impact in two of the geographic cases: when implemented in a region of high pig farming density located near Natura 2000, and when implemented in a region of high pig farming density located far from Natura 2000 areas. Slurry acidification and slurry separation achieved sizeable abatement potential for impacts on ecosystem quality, but incurred large additional costs in all geographic case studies considered, particularly when arable land was limited near the pig farm.

Accounting for basic spatial characteristics within an environmental abatement cost framework had significant impact on the cost-effectiveness of on-farm investments for mitigation of system

environmental impact. To date, no studies have utilised such spatial characteristics within environmental abatement cost modelling of livestock farming systems. The presented framework has the potential to be further expanded using more detailed spatial, economic and geophysical data, which could ultimately improve decision making regarding cost-effective investments that aim improve the sustainability of livestock farming operations.

5.1. Introduction

Life cycle assessment (LCA) models have been commonly used to evaluate potential environmental impacts associated with the operation of livestock systems, by assessing nutrients flows through the farming system as a whole. These assessments typically use generic, global emission characterisation factors (Guinée & Lindeijer, 2002); however, the importance and relevance of these impact categories can be significantly affected by spatial variability (e.g. topography, soil type, precipitation) (Basset-Mens, Anibar, Durand, & Van der Werf., 2006a; Potting, Hertel, Schöpp & Bastrup-Birk, 2006; Roy, Deschênes & Margni, 2014a). Failure to account for such uncertainties can lead to inaccurate and misleading estimates of potential impacts (Azevedo, Henderson, van Zelm, Jolliet & Huijbregts, 2013b), particularly when comparing the effectiveness of potential farm investments that aim to reduce system environmental impact (Pexas et al., 2020a).

Recent major projects like the IMPACT World+ (http://www.impactworldplus.org) (Bulle et al., 2019) have attempted to provide spatially explicit characterisation factors on a global scale, mainly for the assessment of eutrophication potential, acidification potential, land use and water footprint (water scarcity) associated with specific nitrogen and phosphorus emissions. Other studies have proposed ways to integrate geographic information system tools (GIS) in LCA to account for the effect of spatial differentiation on pollutant transportation and fate (Azevedo et al., 2013a; Henryson, Hansson & Sundberg, 2018).

In addition to environmental implications, geography can also affect the economic performance of pig production systems. Variability in feed, fuel and construction material prices across the spatial dimension can result in large variations in on-farm operating costs. Regulations and restrictions imposed by regionalised policies for environmental pollution mitigation (i.e. Nitrates Directive, Water Framework Directive) can cause significant increases in slurry transportation costs and may require additional farm investments for manure treatment (Fealy &

Schröder, 2008; Jacobsen, Latacz-Lohmann, Luesink, Michels & Ståhl, 2019). Pig farm density at regional level can affect the feasibility and cost-effectiveness of potential farm investments (e.g. anaerobic digestion) through agglomeration effects, including knowledge and input sharing, and specialised labour supply that can improve farm technical efficiency and profitability (Cohen & Paul, 2005; Larue, Abildtrup & Schmitt, 2011). Therefore, it is necessary that the potential geographic variability of economic parameters is addressed whenever possible, particularly when cost-effectiveness assessments are used to guide decision-making regarding strategies that aim to improve system sustainability, and shape policies on a broader spatial scale (Ciroth et al., 2002; Pexas et al., 2020b).

Pig production in Denmark was utilised as a case-in-point to investigate the potential for integration of spatial data in methods that facilitate decision making for environmental abatement strategies. Pig production is regarded among the largest contributors to acidification of ecosystems and eutrophication of freshwater bodies arising from livestock and Denmark is the world's largest pork meat exporter (De Vries & De Boer, 2010). Danish pig production primarily occurs in Jutland an area of relative topographic and climatic homogeneity (Larue, Abildtrup & Schmitt, 2007). However, a large part of this land is covered by nature sensitive areas designated to protect various species and habitats (i.e. Natura 2000 areas) (Jacobsen et al., 2019). Moreover, the country is characterised by large regional variability in pig production intensity (Larue et al., 2007).

The specific aim of this study was to develop a spatially explicit, environmental abatement cost framework to assess and compare the cost-effectiveness of alternative manure management strategies that aim to reduce the environmental impact of pig farming systems, when implemented in a range of geographic case studies. In doing so, the study investigated differences in system environmental performance across different locations for several potential impact categories, using spatially explicit environmental impact characterisation factors. Additionally, it evaluated effects of topographic variability on the economy of the system by accounting for variations in manure transportation and application regimes associated with the implementation of each manure management strategy.

5.2. Materials and Methods

A bottom-up, technology based, environmental abatement cost approach was followed and integrated with spatial information to achieve the goal of this study. The analyses were carried out through the following steps:

i) The operation of one pig farming system was simulated with the implementation of four different manure management strategies: the baseline and three alternatives that target reductions in system environmental impact.

ii) Scenarios were developed to simulate the operation of the pig production system with the implementation of the above manure management strategies in four different locations across our study area.

iii) A 4 x 4 scenario analysis was designed to estimate the annualised system environmental impact for a range of impact categories, through a spatially explicit environmental LCA framework.

iv) The same scenario analysis design was used to estimate whole-farm annualised financial performance metrics derived from a discounted cash flow analysis over a 25-year time horizon.

v) Finally, the cost-effectiveness of each manure management strategy in reducing system environmental impact was assessed and the effect of spatial variability on it was evaluated.

5.2.1. Goal and scope of environmental life cycle assessment

A cradle-to farm gate, life cycle impact assessment framework was developed in SimaPro 8.5.0.0 (PRé Consultants, Amersfoort, The Netherlands) according to Pexas et al. (2020a). The goal of the framework was to simulate the operation of the typical Danish integrated pig farming system, under baseline manure management conditions and with each of the alternative manure management strategies implemented.

Within the system boundaries (Fig. 5.2) the study modelled: i) feed production (i.e. diet formulations used), ii) animal growth at pig barn across the four production stages, and iii) manure management at pig barn, storage and field. The functional unit of the analysis was the production of 1 kilogram of live weight pig at slaughter weight adjusted for mortality rates.

5.2.2. Life cycle inventory

Pig farming system description

Analyses were performed on a typical, integrated Danish pig farming system, which reared pigs that were offspring of Danish Landrace x Yorkshire sows and Duroc sires (Pexas et al., 2020b). The production system comprised four distinct stages: i) gestation (gestating sows), ii) lactation (lactating sows and suckling piglets), iii) nursery (weaners < 30 kg) and iv) growing/finishing (pigs reared until slaughter weight and replacement gilts). It followed a three-week batch farrowing system and produced approximately 13,100 slaughterpigs annually. For each production stage, the pig housing system consisted of an indoor, mechanically ventilated building that complied with the Best Available Techniques (BAT) guidelines for rearing of pigs (Santonja et al., 2017). The study considered the use of six different diet formulations across the four production stages: gestating sow diet, lactating sow diet, nursery diet from 6.7 kg to 15 kg, nursery diet from 15 kg to 30 kg, growing diet from 30 kg to 65 kg and finishing diet from 65 kg to slaughter weight (Tybirk et al., 2016). Potential environmental impacts associated with the production of individual feed ingredients and the preparation of diet formulations were considered in the analysis (Pexas et al., 2020a).

Methane (CH_4) emissions and nutrient excretion (N, P, K) associated with animal growth within the pig farming system were calculated following the mass balance principle, tracing nutrient flows throughout the production stages. The effects of ambient temperature on indoor climate parameters, energy consumption for climate control and CH_4, NH_3, NO_x and N_2O emissions were also accounted for in the description of the system (Pexas et al., 2020a). The same approach was used to model CH_4, NH_3, NO_x, N_2O and N_2 emissions from slurry at pig housing (pen and slurry pits), slurry storage and field application. Specific emission factors for chemical substances associated with the operation of the production system were obtained by IPCC guidelines (Dong et al., 2006), the IMPACT World+ project (Bulle et al., 2019), and relevant literature (Nguyen, Hermansen, & Mogensen, 2011; Pexas et al., 2020b).

Manure management strategies

Baseline practice

Under baseline conditions, manure was stored outside, in concrete covered slurry tanks, and applied by trail-hose tanker to replace synthetic fertiliser for crop production. The 75% nutrient substitution rate for nitrogen, 97% for phosphorus and 100% for potassium, were used to estimate the amount of manure applied as organic fertiliser, (Nguyen et al., 2011).

In addition to the baseline scenario, the study modelled the system with the implementation of the three most commonly adopted alternative manure management strategies with potential to reduce the environmental impact of pig farming systems (Ten Hoeve et al., 2014; Pexas et al., 2020a).

Anaerobic Digestion (AD)

For this scenario, the co-digestion of pig slurry with grass silage (80:20 w/ w) was simulated on-farm, for biogas production. Electricity and heat was generated by the bio-methane yield at a combined heat and power plant (CHP) that operated at 80% efficiency, and was discounted from on-farm energy use. Upon treatment, the nutrient enriched digestate was applied in the fields under baseline conditions (trail-hose tanker), but with an increased fertiliser efficiency; substitution rates were for N: 85% and P: 100% (Vega et al., 2014).

Slurry Acidification (Acid)

Slurry acidification was simulated as an automated process that took place in an acidification plant adjacent to the pig housing facilities. During the treatment phase, slurry was pumped from the pits to the plant where it was acidified, mixed and then pumped back to the slurry pits. The acidified slurry was stored and applied under baseline conditions (Kai et al., 2008; Fangueiro et al., 2015). For this manure management strategy, 9.7 kg of highly concentrated sulphuric acid (96% H_2SO_4) and 15 kg of calcium carbonate ($CaCO_3$) per tonne of slurry were required, as well as an additional 3 kWh per m^3 of slurry acidified of energy required for the mixing (Ten Hoeve et al., 2016).

Screw Press Separation (SP)

The separation of slurry by screw press was simulated as a process that occurred at manure storage. Upon separation, the liquid fraction was stored and applied under baseline conditions. The solid fraction was piled on-farm and applied by broadcast spreading and rapid incorporation. The substitution rate for N was different for the two fractions with N_{liquid} at 75% and N_{solid} at 65% (Ten Hoeve et al., 2014).

5.2.3. *Geographic case studies and spatial analysis*

Four location scenarios were developed to account for spatial variability in environmental and economic impact associated with the operation of the pig production system, as well as to address potential effects of spatial differentiation on the cost-effectiveness of the alternative manure management strategies.

Aside from addressing topographic variability through spatially explicit characterisation factors, the study also considered the following two spatial parameters for the development of the four geographic case studies: i) proximity of pig farm to nature sensitive areas (Natura 2000 network) and ii) pig farming density at municipality level. If a pig farm was located closer than 400 m from a Natura 2000 area, it was considered to be 'at close proximity' to nature sensitive areas (Jacobsen et al., 2019). The 'distance from Natura 2000 areas' criterion was evaluated by performing a buffer analysis for Natura 2000 areas contained within the extent of Danish administrative boundaries.

Spatial zones that meet each possible combination of the spatial criteria above were identified in Jutland, Denmark. Four locations were randomly selected within those spatial zones, to provide context for the spatially explicit environmental abatement cost analysis (Fig. 5.1a-5.1b):

i) '*N-LD*': located at 57° 4.0669 N, 9° 44.7008 E, characterised by close proximity to Natura 2000 areas (< 400 m) and in a region of 2-3 pig farms per hectare.

ii) '*N-HD*': located at 56° 41.6027 N, 8° 38.1546 E, characterised by close proximity to Natura 2000 areas (< 400 m) and in a region of 7-9 pig farms per hectare.

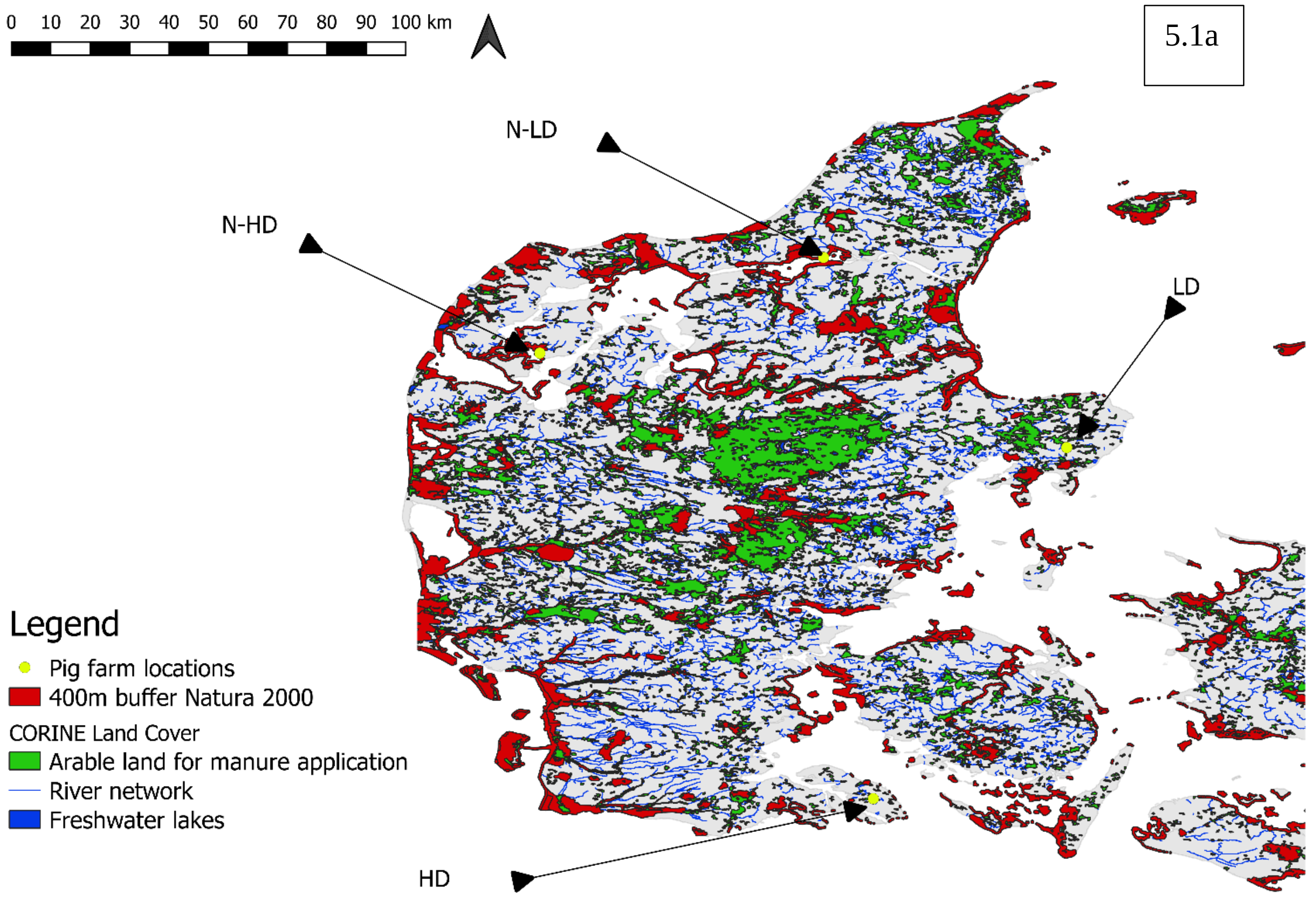
iii) '*LD*': located at 56° 19.4616 N, 10° 41.7729 E, at a distance from Natura 2000 areas (> 2 km) and in a region of 2-3 pig farms per hectare.

iv) '*HD*': located at 54° 57.057 N, 9° 56.378 E, at a distance from Natura 2000 areas (> 2 km) and in a region of 7-9 pig farms per hectare.

For each of the above case studies, a radial analysis was performed using 1 km increments and the farm coordinates as the geocentre, to determine the availability of arable land for manure application in areas surrounding the farm. The required transportation distance for manure to be applied in arable land was estimated according to the Danish Regulation of Nutrients in Agriculture & the Danish Nitrates Action Programme, which specifies an allowance of 170 kg N ha^{-1} y^{-1} and a ceiling of 35 kg P ha^{-1} y^{-1} (Ministry of Environment and Food of Denmark, 2017).

According to Danish Environmental Agency, the maximum allowance for nitrogen deposition in ammonia sensitive habitats such as Natura 2000 areas, is below 0.2 kg ha^{-1} y^{-1} per pig farm in cases where more than one neighbouring farms are located within 1 km radius from the system under assessment. If there are no neighbours within the 1 km radius, then the maximum allowance is below 0.7 kg ha^{-1} y^{-1} per pig farm. The neighbouring distance depends on the size of the farms. This study assumed the neighbouring farms would be of the same size, 500-sow integrated pig farming systems, which corresponds to the 1 km distance threshold (Jacobsen & Ståhl, 2018; Jacobsen et al., 2019). Therefore, for regions with 7-9 pig farms per hectare (cases HD and N-HD) we assumed the lower maximum allowance and that the available arable land would be shared between at least three pig farms, while for regions with 2-3 pig farms ha^{-1} we assumed the higher allowance and no neighbours to share land for manure application. Such variability in manure application related factors could have implications in system environmental and economic performance, particularly when evaluating the cost-effectiveness of strategies that directly affect manure composition.

Spatial analysis was performed in QGIS 3.10.9 'A Coruña' (QGIS.org, 2020), with data obtained from the European Environmental Agency (EEA, available at https://www.eea.europa.eu/data-and-maps/data/natura-11/natura-2000-spatial-data) and CORINE Land Cover 2018 (Coordination of Information of the Environment, available at https://www.copernicus.eu/en). Pig farm density data were obtained from the Danish Statistics Agency (Statbank Denmark, available at www.statbank.dk/BDF51).


5.1a
0 10 20 30 40 50 60 70 80 90 100 km
N-LD
N-HD
LD
HD
Legend
Pig farm locations
400m buffer Natura 2000
CORINE Land Cover
Arable land for manure application
River network
Freshwater lakes

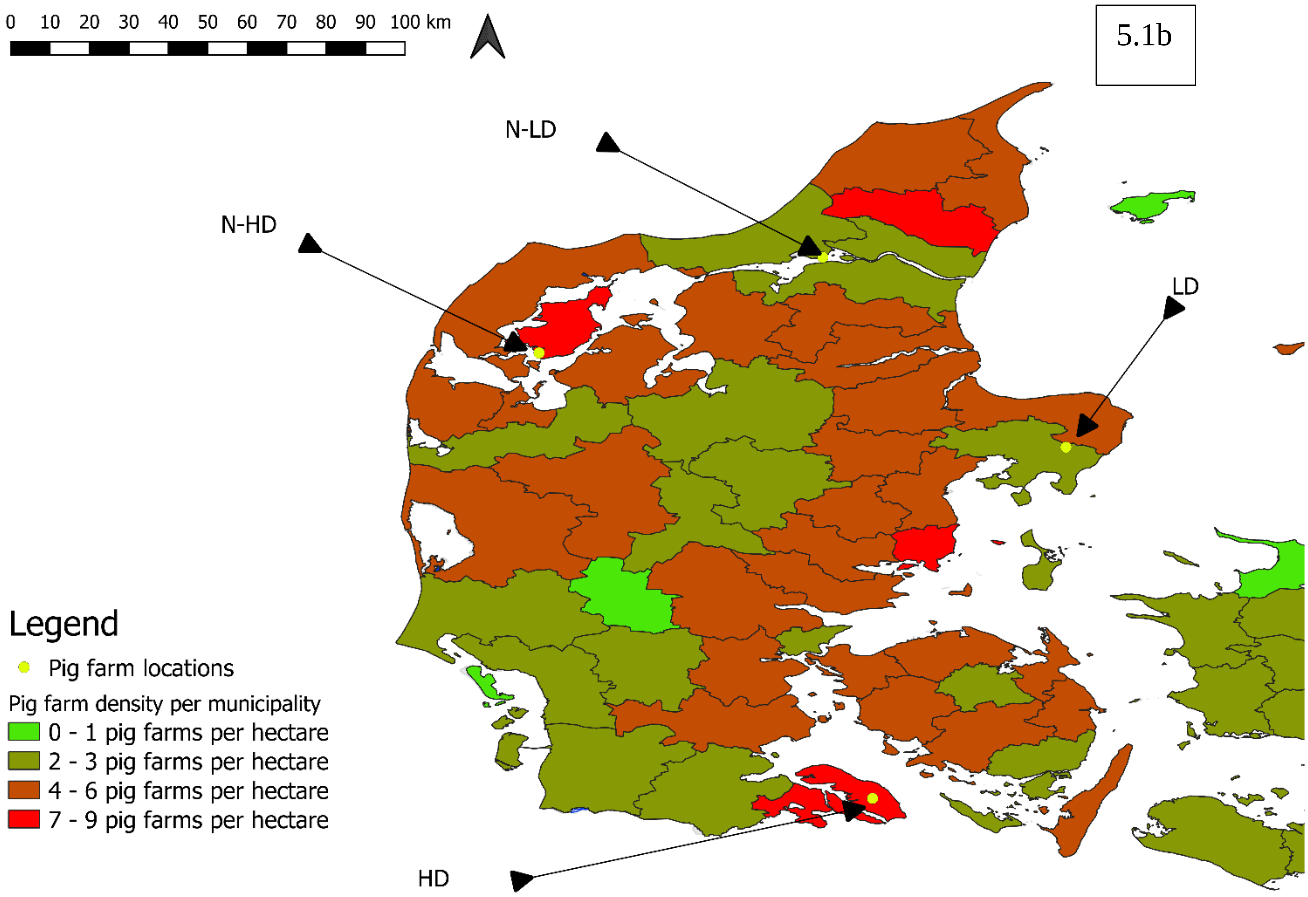


Figure 5.1a-5.1b.: Four pig farm locations in Jutland, Denmark. The top map presents areas within the Danish administrative boundaries covered by arable land and Natura 2000 protected areas (including 400 m buffer); freshwater lakes and the Danish river network are also included. The bottom map presents pig farm density at a municipality level. N-LD = Case study less than 400m from Natura 2000 and in region of 2-3 pig farms per hectare. N-HD = Case study less than 400m from Natura 2000 and in region of 7-9 pig farms per hectare. LD = Case study further than 2km from Natura 2000 and in region of 2-3 pig farms per hectare. HD = Case study further than 2km from Natura 2000 and in region of 7-9 pig farms per hectare

5.2.4. Environmental life cycle impact assessment

The annualised environmental impact of the pig production system was calculated as the summation of the equally weighted environmental impacts for each production stage within the cradle-to-farm gate system boundaries. The environmental impact categories assessed were chosen based on FAO guidelines for the environmental impact assessment of pig supply chains (FAO, 2018a) and the FAO guidelines for water use in livestock production (FAO, 2018b). To account for spatial variability in system environmental impact across different geographic case studies, the study adapted the IMPACT 2002+ v2.14 and ReCiPe 2016 Midpoint v1.01 impact calculation methods by using spatially explicit factors derived from the IMPACT World+ project (Bulle et al.,

2019) (Table 5.1). The specific impact categories assessed were *Aquatic Acidification Potential* (AAP) and *Terrestrial Acidification Potential* (TAP) expressed in tonnes of sulphate (SO_2^-) equivalents, *Marine Eutrophication Potential* (MEP) expressed in kg of nitrogen (N) equivalents, and *Freshwater Eutrophication Potential* (FEP) expressed in tonnes of phosphate (PO_4^{3-}) equivalents. System water footprint was also estimated using spatially explicit characterisation factors through the *Available Water Resources* (AWARE v1.01) method expressed in cubic metres of water used (m^3). The CML Baseline v3.05 calculation method was used to estimate *Non-Renewable Resource Use* (NRRU) expressed in kg of antimony (Sb) equivalents, *Non-Renewable Energy Use* (NREU) expressed in mega-joules (MJ) and *Global Warming Potential* (GWP) expressed in kg of carbon dioxide (CO_2) equivalents. Each environmental impact category was assessed individually in this analysis; we did not aggregate across categories.

A Monte Carlo (MC) method (1000 iterations) was used for the quantification of uncertainties related to data inputs and to distinguish between uncertainties specific to each scenario or shared between scenarios. Statistical significance of differences when comparing between scenarios was evaluated at a=5%. (Mackenzie et al., 2015; Pexas et al., 2020b). Whenever uncertainty information was not available for variables relevant to any of the scenarios, the variable was assumed to be normally distributed with a standard deviation equal to 10% of the mean (Groen et al., 2014a; 2014b). The abatement potential of an alternative strategy was estimated as its difference in environmental impact for each individual category when compared to the baseline.

Table 5.1.: Spatially explicit characterisation factors for the assessment of Aquatic Acidification Potential, Terrestrial Acidification Potential, Freshwater Eutrophication Potential, Marine Eutrophication Potential and Available Water Resources. The characterisation factors were obtained from the IMPACT World+ project (Bulle et al., 2019). The impact category and the substance contributing to it is presented for geographic case studies of pig production in Denmark. N-LD = Case study less than 400m from Natura 2000 and in region of 2-3 pig farms per hectare. N-HD = Case study less than 400m from Natura 2000 and in region of 7-9 pig farms per hectare. LD = Case study further than 2km from Natura 2000 and in region of 2-3 pig farms per hectare. HD = Case study further than 2km from Natura 2000 and in region of 7-9 pig farms per hectare

Impact category - Substance	Unit	N-LD	N-HD	LD	HD
Aquatic Acidification - Nitric acid	kg SO_2^- eq.	1.14 E-06	1.14 E-06	7.54 E-08	1.14 E-06
Aquatic Acidification - Nitrogen oxides	kg SO_2^- eq.	1.56 E-06	1.56 E-06	1.03 E-07	1.56 E-06
Aquatic Acidification - Ammonia	kg SO_2^- eq.	5.64 E-06	5.64 E-06	1.73 E-07	5.64 E-06
Aquatic Acidification - Sulphur dioxide	kg SO_2^- eq.	4.37 E-06	4.37 E-06	1.65 E-07	4.37 E-06
Terrestrial Acidification - Sulphur dioxide	kg SO_2^- eq.	0.00616	0.00616	0.000734	0.00616

Terrestrial Acidification - Nitrogen oxides	kg SO_2^- eq.	0.00192	0.00192	0.000341	0.00192
Terrestrial Acidification - Ammonia	kg SO_2^- eq.	0.0151	0.0151	0.000749	0.0151
Freshwater Eutrophication - Phosphorus	kg PO_4^{3-} eq.	0.00856	0.000797	0.00774	0.00999
Freshwater Eutrophication - Phosphate	kg PO_4^{3-} eq.	0.00280	0.000261	0.00253	0.0326
Marine Eutrophication - Nitrogen oxides	kg N eq. kg^{-1}	0.0530	0.0530	0.0524	0.0530
Marine Eutrophication - Ammonia	kg N eq. kg^{-1}	0.226	0.226	0.449	0.226
Available Water Resources - Water use	m^3 world eq.	0.880	0.494	2.27	0.768

5.2.5. Economic model

The economic performance of the pig farming system with the implementation of each manure management strategy was evaluated through a discounted cash flow analysis over a 25-year time horizon (Pexas et al., 2020a). This approach was consistent with the Life Cycle Cost Analysis method, although due to data limitations we assumed a zero end-of-life disposal value of capital equipment (Norris, 2001). A comprehensive list of economic data was compiled by SEGES, to describe all relevant processes. Table 5.2 summarizes the main costs associated with the implementation of each manure management scenario. For the analysis, we used a long-term investment discount rate of 2.83% (Pexas et al., 2020a).

Capital costs were calculated and amortised over a 25-year lifetime for building-related components and a 12.5-year lifetime for technological equipment. Technological reinvestments were considered for equipment that was expected to be renewed at intervals more frequent than the time horizon. Costs related to the pig housing (i.e. building infrastructure, climate control, feed & water delivery and slurry removal technological equipment) and manure management component i.e. slurry storage and field application equipment) were considered. Working capital included the purchasing of breeding stock.

Operational expenses included animal, pig housing management and manure management related costs. Specifically, they included feed, veterinary / medical inputs, electricity and diesel fuel, technological equipment maintenance and labour. The study accounted for variability in costs associated with the transportation and application of manure that had been treated with any of the alternative manure management strategies considered.

Total revenues consisted of live weight pig meat sold and avoided costs of synthetic fertiliser at crop production replaced by the field application of manure.

Two farm financial metrics commonly used to compare the economic performance of alternative investments were employed for the assessment of investment feasibility in the different location scenarios. Whole-farm Annual Equivalent Value (AEV) was used as a measure of the annualised monetary returns and a proxy to estimate annual farm profitability (Eq. 5.1). The second was the Internal Rate of Return (IRR), which represents an investment's expected percentage return on capital over the time horizon.

$$(\mathbf{Eq. 5.1})\ AEV = \frac{d(NPV)}{1-(1+d)^{t}}$$

Where, d = discount rate, t = total number of years in time horizon, NPV = farm Net Present Value calculated through the discounted cash flow.

Table 5.2.: Main costs of categories associated with the implementation of the baseline and alternative manure management strategies on a typical integrated Danish pig farm. AD = Anaerobic Digestion. Source: Pexas et al. (2020b)

Cost category	Unit	Cost
Diesel fuel	€ per litre	1.35
Electricity from the national grid-household price	€ per kWh	0.100
Electricity from natural gas	€ per kWh	0.0912
Labour, wage	€ per hour	22.5
Acidification plant (incl. pumping system)	€ per unit	16,495
Sulphuric acid 96% (H_2SO_4) per kg	€ per kg	0.0673
Calcium carbonate ($CaCO_3$)	€ per kg	0.102
Total on-farm AD project costs (incl. connection to grid & other fees)	€ per unit	556,833
Total on-farm AD operating expenses (incl. labour, co-substrate, maintenance)	€ per m^3 manure treated	14.2
Screw press separator (incl. mixer, separator, controls, pumping system)	€ per unit	36,913
Manure application with broadband spreading and rapid incorporation	€ per m^3 manure	2.00

5.2.6. Cost-effectiveness assessment

Upon estimation of the annualised system environmental and economic impacts, the cost-effectiveness of each manure management strategy was calculated separately for the different environmental impact categories considered through Equation 5.2. Figure 5.2 provides a schematic representation of how the environmental LCA, economic model and spatial information connect within the spatially explicit cost-effectiveness framework.

$$(\mathbf{Eq. 5.2})\ €\, per\ unit\ of\ pollutant\ abated = \frac{\Delta AEV}{\Delta EI} \times (-1)$$

Where, ΔAEV = difference in whole-farm annual equivalent value between baseline and alternative manure management strategies and ΔEI = difference in environmental impact between baseline and alternative manure management strategy.

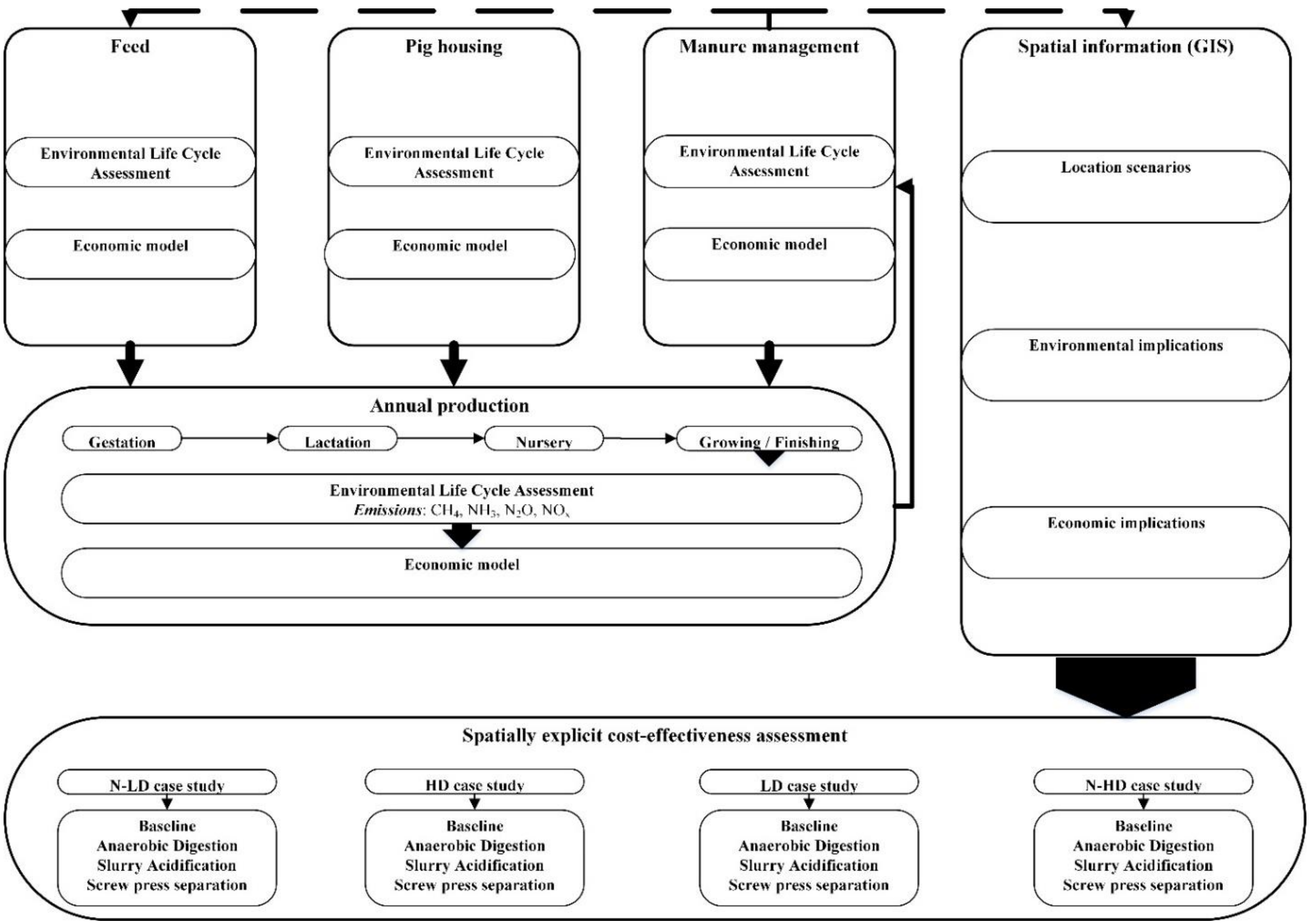


Figure 5.2.: Main components and flows within the system boundaries of the spatially explicit cost-effectiveness analysis. Solid arrows represent connections between the individual environmental, economic and spatial models. Dashed arrows illustrate discounts in synthetic fertiliser for crop production and that manure application regimes provide context for the spatial analysis. We considered energy use (electricity, natural gas, diesel fuel) in all relevant processes within the system boundaries. GIS = Geographic Information Systems. N-LD = Case study less than 400m from Natura 2000 and in region of 2-3 pig farms per hectare. N-HD = Case study less than 400m from Natura 2000 and in region of 7-9 pig farms per hectare. LD = Case study further than 2km from Natura 2000 and in region of 2-3 pig farms per hectare. HD = Case study further than 2km from Natura 2000 and in region of 7-9 pig farms per hectare

5.3. Results and Discussion

5.3.1. Manure management strategies and manure chemical composition

Prior to the environmental LCA and economic assessment, the amounts of nitrogen and phosphorus available for field application annually were estimated for each manure management strategy considered. Under baseline conditions, a total of approximately 26,664 kg N y^{-1} and 8,149 kg P y^{-1} were available for application as organic fertiliser. Anaerobic digestion of slurry resulted in an enriched digestate with higher nutrient concentrations of 47,490 kg N y^{-1} and 8,413 kg P y^{-1}. When slurry was acidified, the resulting manure also contained higher amounts of nitrogen than the baseline scenario at 36,950 kg N y^{-1} and 8,149 kg P y^{-1}. Finally, when screw press separation was implemented the total amount of nitrogen available for application reduced at 22,520 kg N y^{-1} and 8,149 kg P y^{-1}. The large differences in nitrogen concentrations of manure between the various manure management strategies were observed due to the different mitigation potential achieved for nitrogen related emissions by each strategy. Anaerobic digestion and slurry acidification significantly mitigated ammonia, dinitrogen monoxide and nitrogen emissions at pig housing and manure storage, and therefore resulted to higher amounts of nitrogen in manure. Phosphorus concentrations in manure were only affected with the implementation of anaerobic digestion, where it increased as a consequence of the co-digestion with grass silage process. While slurry separation allows for nutrient redistribution, the amount of total phosphorus at the end of the process is the same as prior its implementation.

Arable land requirements for manure application under Danish legislation (170 kg N ha^{-1} y^{-1} and 35 kg P ha^{-1} y^{-1}) were estimated, considering the amount of N and P produced by each manure management strategy as presented above. In cases N-LD and LD, it was found that 157 ha were required for application of manure treated under the baseline strategy, 279 ha for the application of digestate, 217 ha for acidified manure and 133 ha for separated manure. In regions with 7-9 pig farms ha^{-1} (cases HD and N-HD) where land was assumed to be shared between three pig farms, requirements for available land were higher at 471 ha for baseline manure management, 839 ha with anaerobic digestion, 653 ha with slurry acidification and 398 ha with screw press slurry separation. The spatial analysis showed that in N-LD, a 9 km transportation distance of manure was sufficient to meet the arable land requirements for baseline manure management and screw press separation, and 10 km for the anaerobic digestion and slurry acidification strategies. In HD, the required transportation distance was 5 km for the baseline and screw press separation strategies, 6 km for slurry acidification and 8 km for anaerobic digestion. In LD, manure was applied within a 5 km radius with the implementation of any of the manure management strategies. Finally, in N-HD manure transportation distance increased at 15 km under baseline and screw press separation strategies, and 17 km if slurry acidification or anaerobic digestion were implemented. These outcomes reflect variability in land cover types (e.g. arable land, urban surface) of areas surrounding the pig farming system across different localities. Even in a topographically homogeneous country such as Denmark, large differences were observed in the percentage of area covered by arable land between the four geographic case studies tested (Table A5.1). Such differences could be even more relevant in larger countries with greater topographic variability.

The maximum nitrogen deposition allowance in Natura 2000 areas is below 0.2 kg ha^{-1} y^{-1} pig $farm^{-1}$ in cases where more than one neighbouring farms are located within 1 km from the system under assessment, and below 0.7 kg ha^{-1} y^{-1} if there are no neighbouring farms (Jacobsen & Ståhl, 2018; Jacobsen et al., 2019). While this was considered in thestudy, it did not lead to any significant differences in manure application related environmental or economic impacts. Even when a pig farm was located amidst a large Natura 2000 network and in a region of 2-3 pig farms ha^{-1} (i.e. N-LD), the nitrogen deposition allowance did not result in any reductions in the required manure transportation distance.

5.3.2. Environmental life cycle assessment

Figure 5.3a-5.3h presents the annualised system environmental impact under baseline manure management and with the implementation of the alternative strategies considered, across the four geographic case studies and for each impact category separately. Table A5.2 of the Appendix, summarises the mean environmental impact of each scenario, for the impact categories assessed.

Manure management strategies

When compared to the baseline manure management scenario, anaerobic digestion exhibited significant potential to mitigate system environmental impact for several impact categories, which varied across the four geographic locations tested. The abatement potential achieved for TAP by this strategy was 61.9% in N-HD, 62.1% N-LD and HD, and 65.5% in LD. For NREU it exhibited 29.2% abatement potential in N-HD and 30.1% in N-LD, LD and HD. The same pattern was observed for NRRU, which it mitigated significantly by 11.0% in N-HD and 16.6% in N-LD, LD and HD, and GWP, which it significantly reduced by 1.24% in N-HD and 1.52% in the other geographic locations. For mitigation of AWARE, anaerobic digestion exhibited approximately the same, significant abatement potential (1.69%) in all geographic case studies. The opposite trend was observed for AAP (+20.9% to +21.3%) where anaerobic digestion was the worst manure management scenario overall, with 20.9% higher impact in N-HD and 21.3% in N-LD, LD and HD, compared to the baseline manure management. No significant difference in environmental performance for FEP and MEP between this strategy and the baseline.

The implementation of screw press separation resulted in the largest significant reductions overall for AAP (58.8% in N-HD and 58.4% in N-LD, LD and HD) and MEP (2.33% in all geographic locations). Compared to the baseline scenario, screw press separation also achieved sizeable, significant reductions in system environmental performance for NRRU (5.18% in N-HD and 6.43% in the other geographic case studies). In some geographic locations, smaller but also significant reductions were observed for mitigation of FEP (3.51% in N-HD and 3.71% in HD) and TAP (2.93% in LD). This manure management scenario performed significantly worse than the baseline for GWP (7.84% in N-HD and 7.97% in the other locations), while no significant differences were found in environmental performance for AWARE.

The largest, significant abatement potential of the slurry acidification strategy was observed for AAP (45.7% in N-HD and 45.9% in all other locations), TAP (1.88% in N-HD, 1.92% in N-LD and HD) and MEP (0.126% in N-LD, LD and HD) compared to the baseline. Under this manure management scenario, the worst system environmental performance overall was observed for NREU with 1.55% significantly higher impact in N-HD and 1.38% in all other locations, GWP with +9.48% in N-HD and 9.33% in the rest of case studies, and NRRU with 11.2% higher impact in N-HD and 7.37% in N-LD, LD and HD. Finally, no significant differences were found in environmental performance between the baseline scenario and slurry acidification for FEP and AWARE.

The outcomes of the environmental impact assessment for the different manure management scenarios were anticipated according to the outcomes of the previous studies in this thesis (Pexas et al., 2020a; 2020b). Anaerobic digestion consists of complex processes that lead to the generation of electricity and heat, which is used on-farm to reduce energy consumption at various stages of the operation of the pig production system and therefore mitigate system carbon footprint and the potential for depletion of fossil fuel (Cherubini et al., 2015). Besides these environmental benefits, the co-digestion process returns a nutrient enriched digestate that although more efficient as fertiliser than untreated manure, can intensify acidification (terrestrial and aquatic) and eutrophication related problems (Vega et al., 2014).

Separation of slurry by screw press is a popular manure management strategy used to facilitate nutrient re-distribution through the storage and application of the liquid and solid fractions of slurry by different methods i.e. storage of solid fraction in piles and broadcast spreading with rapid incorporation at field (Ten Hoeve et al., 2014). Because of such differences nitrogen related emissions can be affected with the implementation of slurry separation, particularly when these are combined with good agricultural practices at the relevant stages, for example covering of the solid fraction piles to further reduce ammonia emissions (Ten Hoeve et al., 2016).

Slurry acidification significantly reduced system environmental impact for categories that are largely affected by nitrogen related emissions, such as AAP, TAP, and MEP. Slurry acidification is commonly implemented in the larger pig farming systems of Denmark, to help reduce ammonia emissions at pig housing, manure storage and field application. However, the use of highly concentrated sulphuric acid and energy required for the processes of mixing and pumping results in an increased system environmental impact for the GWP, NRRU and NREU categories (Kai et al., 2008; Fangueiro et al., 2015). The study acknowledges that throughout the process of slurry acidification many volatile sulphuric components can be formed that have potential adverse effects on the animals and the environment (Borst, 2001), which were not accounted for here. The addition of calcium carbonate at field application helps mitigate some of these negative acidic effects but also increases system environmental impact for the NRRU category (Saue & Tamm, 2018).

Effect of location on environmental impact of manure management strategies

In many cases, the spatially explicit environmental life cycle analysis revealed significant effects of location on system environmental impact. The findings showed that system performance for GWP, NREU and NRRU was significantly higher in N-HD than any other geographic case study and did not differ significantly between cases N-LD, HD and LD, under any manure management strategy tested. Specifically, system environmental impact under baseline manure management significantly increased by +0.326%, +0.685% and +3.50% for each of the above categories respectively in N-HD compared to the other geographic case studies. Baseline manure management was the least sensitive scenario for these impact categories, to geographic variability.

With screw press separation a higher system environmental impact was observed, with increases of +0.195% for GWP, +0.613% for NREU and +4.90% for NRRU. Slurry acidification exhibited a +0.463% increase for GWP, +0.857% for NREU and +7.23% for NRRU. Finally, system performance for the above impact categories was mostly affected by geographic variability when anaerobic digestion was implemented, where an increase of +0.613% for GWP, +2.02% for NREU and +10.4% for NRRU in N-HD compared to the other geographic case studies was observed.

GWP, NRRU and NREU are largely affected by energy consumption at various stages of production, and fuel consumption for manure transportation is an important source of emissions related to such impacts (Lammers et al., 2010a; Pexas et al., 2020b). Therefore, as arable land availability and manure transportation distances change across different geographic case studies, so does system environmental performance in relation to the above impact categories. While in cases N-LD and LD, transporting manure at a distance of 10 km met the requirements for application under Danish legislation, in N-HD the farmer needed to travel longer distances (up to 17 km) to reach the required arable land.

Under baseline manure management, system performance for AWARE was also significantly worse in N-HD (~ +0.350%) than in any other geographic case study. When alternative manure management strategies were implemented no significant effects of location on system performance were observed for AWARE. This could be attributed to that the large uncertainties associated with the calculation of this impact category, particularly when assessing such complex processes, outweighed any observed difference in the specific results.

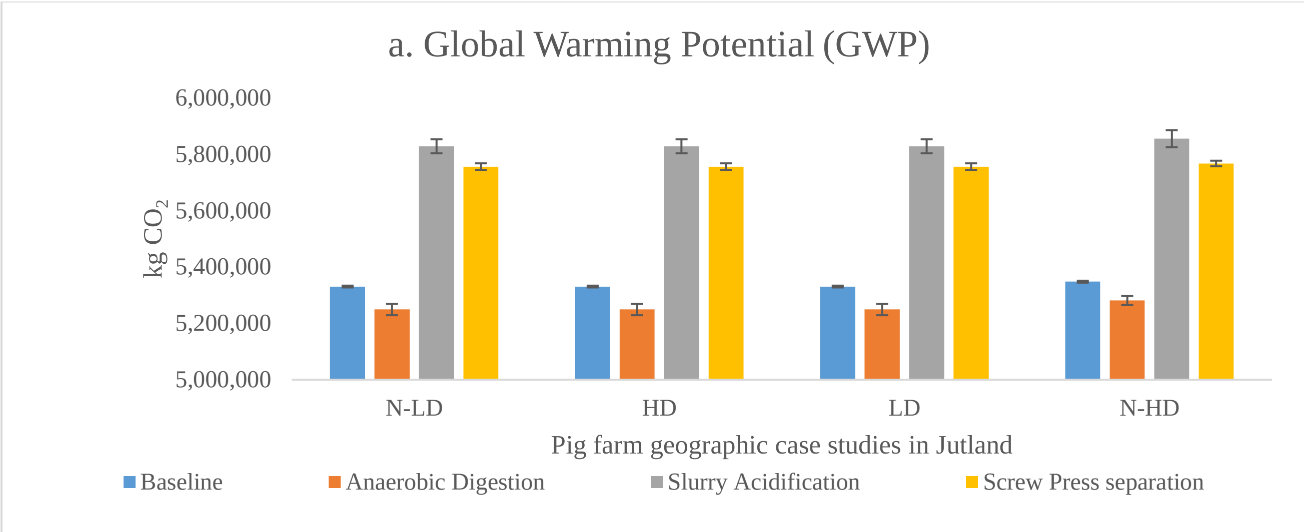
Significant differences were observed also for FEP, which exhibited the largest spatial variability in system environmental performance. With the implementation of anaerobic digestion in HD system impact was 16.5 times higher (59.3 kg PO_4^{3-} eq. y^{-1}) than in N-HD (3.38 kg PO_4^{3-} eq. y^{-1}). In addition, the results showed that performance differences between the various manure management scenarios were larger in HD than in other geographic case studies. For instance, screw press slurry separation exhibited 6.13% lower FEP than anaerobic digestion in HD but only 4.56% lower in N-HD and an even smaller difference of 3.02% lower impact in cases N-LD and LD.

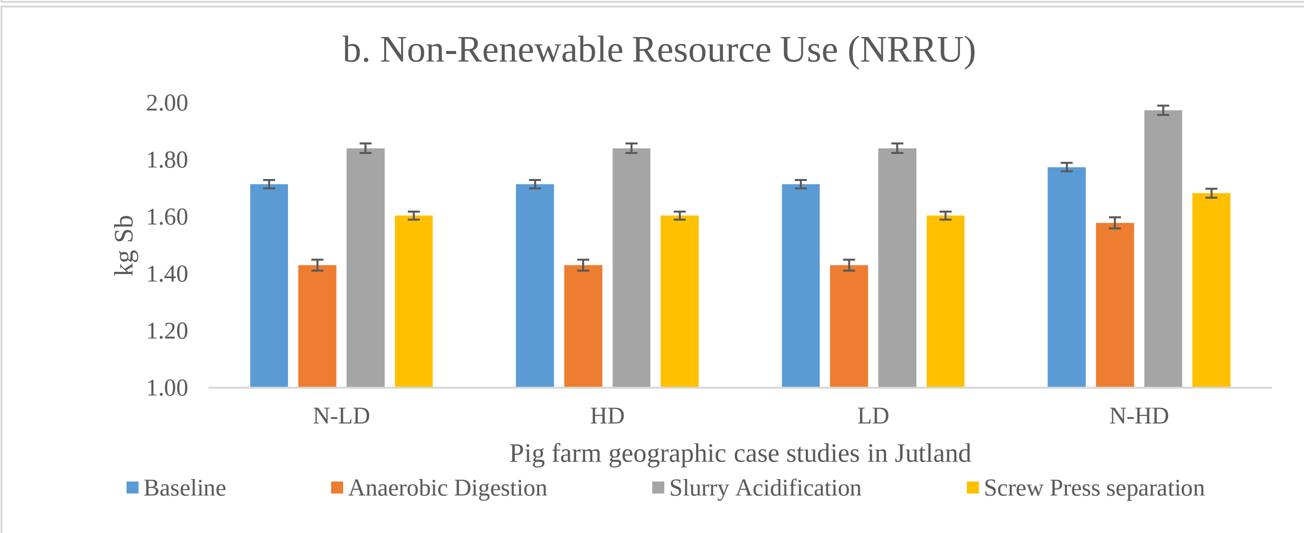
No significant differences were identified in system performance between cases N-LD, HD and N-HD, under any of the manure management scenarios for MEP. However, when the system was located in LD its environmental performance for MEP was significantly higher than in other geographic case studies with differences ranging from +0.197% to +0.245% under baseline manure management, +0.193% to +0.216% with anaerobic digestion, +0.0766% to +0.196% with slurry acidification and +0.196% to +0.246% with screw press separation.

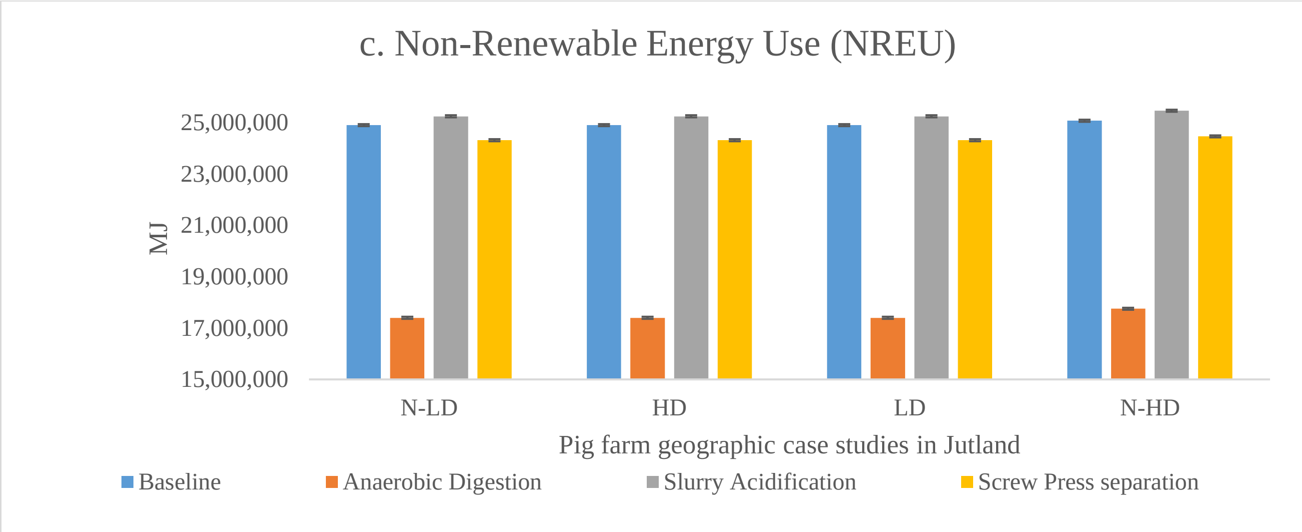
Similarly, for TAP the results did not reveal any significant differences between cases N-LD, HD and N-HD, but system performance was significantly lower in LD than in other geographic cases. Observed differences ranged between -3.98% to -4.03% under baseline manure management, -12.6% to -13.0% with anaerobic digestion, -2.85 with slurry acidification and -6.78% to -6.90% with screw press separation for this impact category.

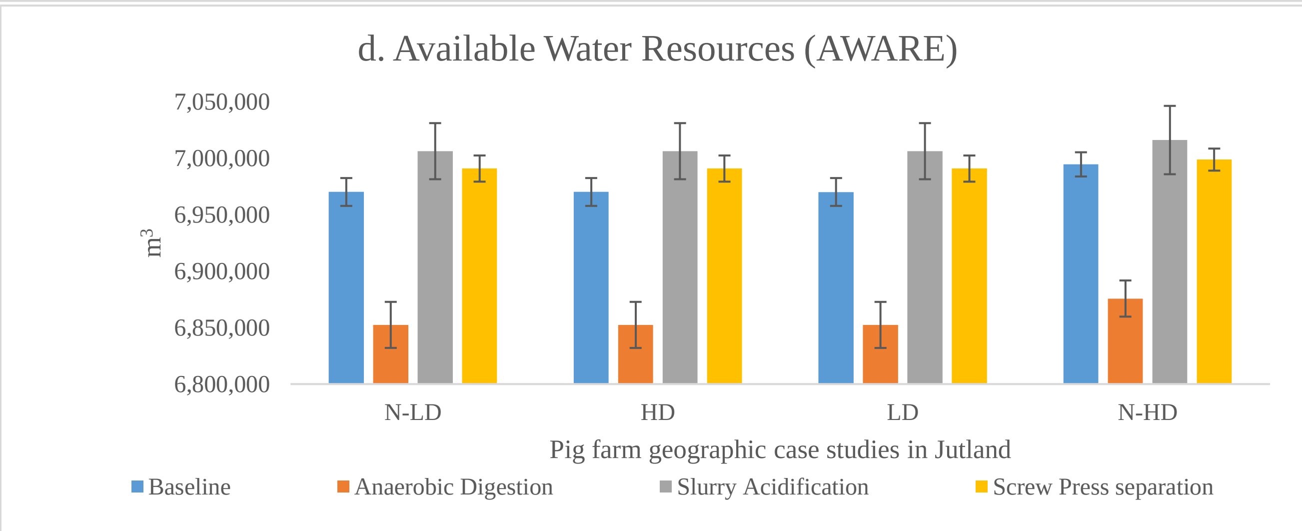
Finally, a significant difference for AAP was only found when anaerobic digestion was implemented, where system performance was significantly lower in N-HD (-0.598% to -0.599%) than any other geographic case studies.

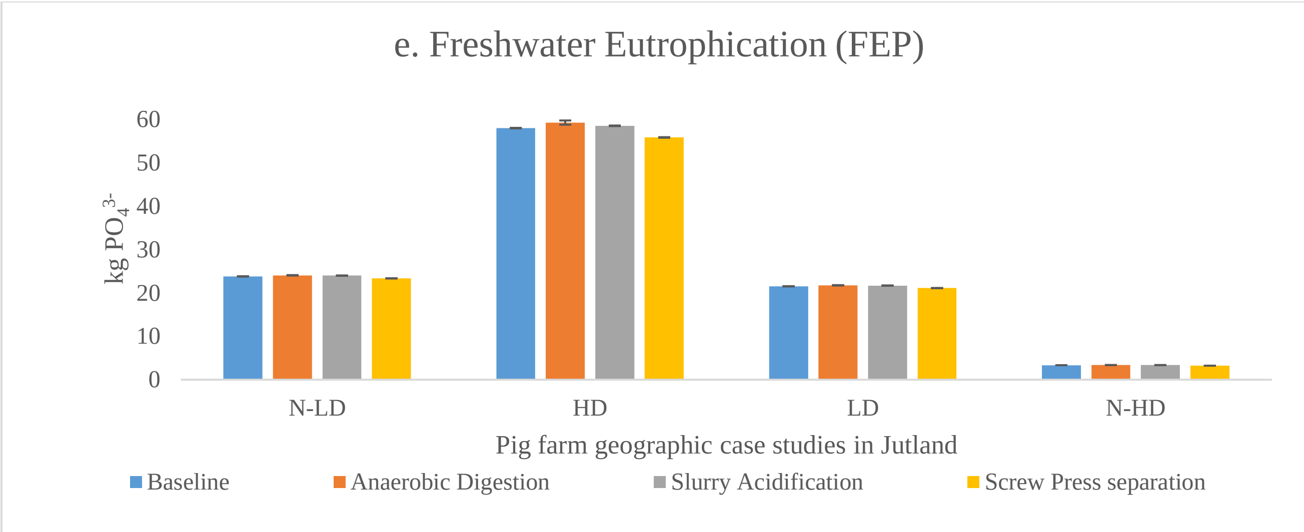
The manure management strategies evaluated in this study all significantly affect airborne, waterborne and emissions to the soil that largely contribute to impacts on ecosystem quality; they do so in diverse ways from one another (Ten Hoeve et al., 2014; Ten Hoeve et al., 2016; Pexas et al., 2020b). Using spatially explicit characterisation factors for most emissions affected by these strategies (Roy et al., 2014b; Henryson et al., 2018), the study highlighted significant spatial effects on system environmental performance for impacts on ecosystem quality, including freshwater and marine eutrophication, and terrestrial and aquatic acidification. The observed differences in environmental performance between geographic locations, respond to the effects of topographic and climatic variability on emission transportation and fate (Bulle et al., 2019).

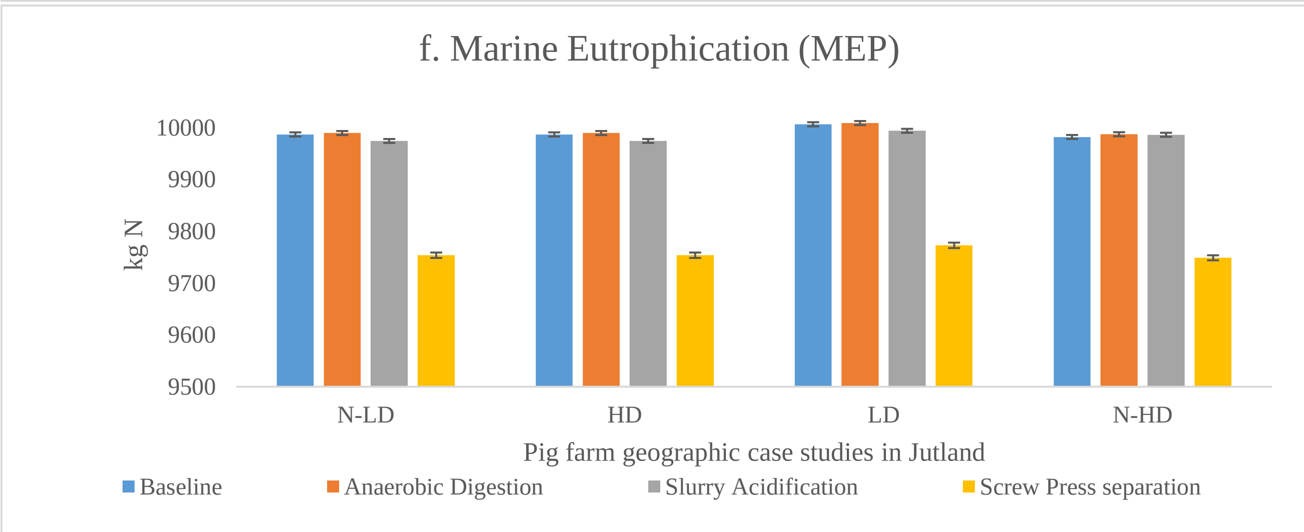

a. Global Warming Potential (GWP)
6,000,000
5,800,000
5,600,000
5,400,000
5,200,000
5,000,000
kg CO_2
N-LD
HD
LD
N-HD
Pig farm geographic case studies in Jutland
Baseline
Anaerobic Digestion
Slurry Acidification
Screw Press separation

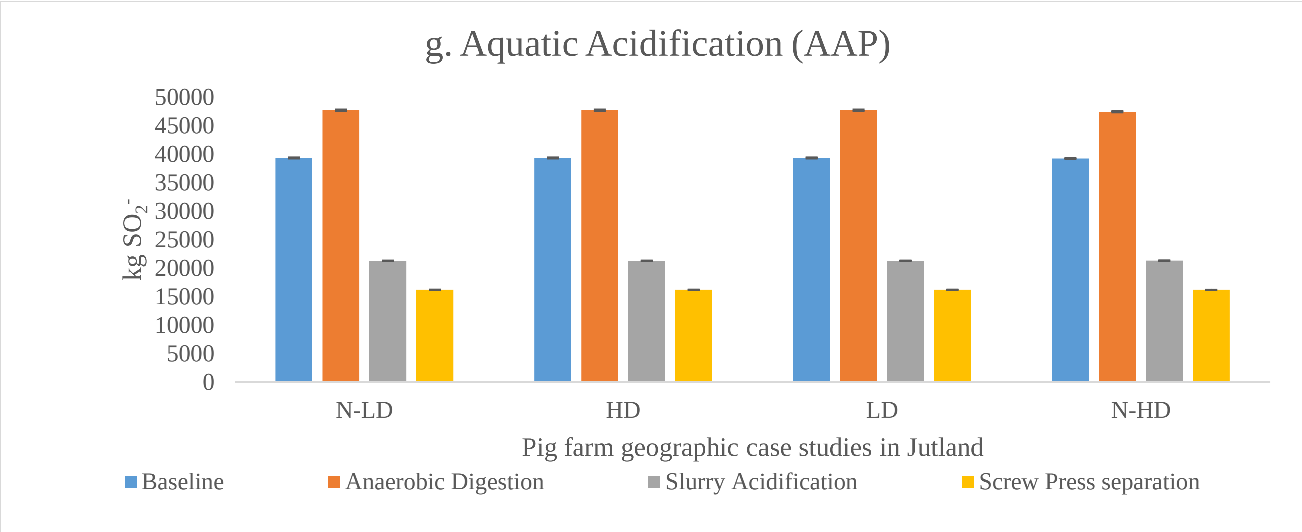

b. Non-Renewable Resource Use (NRRU)
2.00
1.80
1.60
1.40
1.20
1.00
kg Sb
N-LD
HD
LD
N-HD
Pig farm geographic case studies in Jutland
Baseline
Anaerobic Digestion
Slurry Acidification
Screw Press separation


c. Non-Renewable Energy Use (NREU)
25,000,000
23,000,000
21,000,000
19,000,000
17,000,000
15,000,000
MJ
N-LD
HD
LD
N-HD
Pig farm geographic case studies in Jutland
Baseline
Anaerobic Digestion
Slurry Acidification
Screw Press separation


d. Available Water Resources (AWARE)
7,050,000
7,000,000
6,950,000
6,900,000
6,850,000
6,800,000
m3
N-LD
HD
LD
N-HD
Pig farm geographic case studies in Jutland
Baseline
Anaerobic Digestion
Slurry Acidification
Screw Press separation


e. Freshwater Eutrophication (FEP)
60
50
40
30
20
10
0
kg PO_4^{3-}
N-LD
HD
LD
N-HD
Pig farm geographic case studies in Jutland
Baseline
Anaerobic Digestion
Slurry Acidification
Screw Press separation


f. Marine Eutrophication (MEP)
10000
9900
9800
9700
9600
9500
kg N
N-LD
HD
LD
N-HD
Pig farm geographic case studies in Jutland
Baseline
Anaerobic Digestion
Slurry Acidification
Screw Press separation



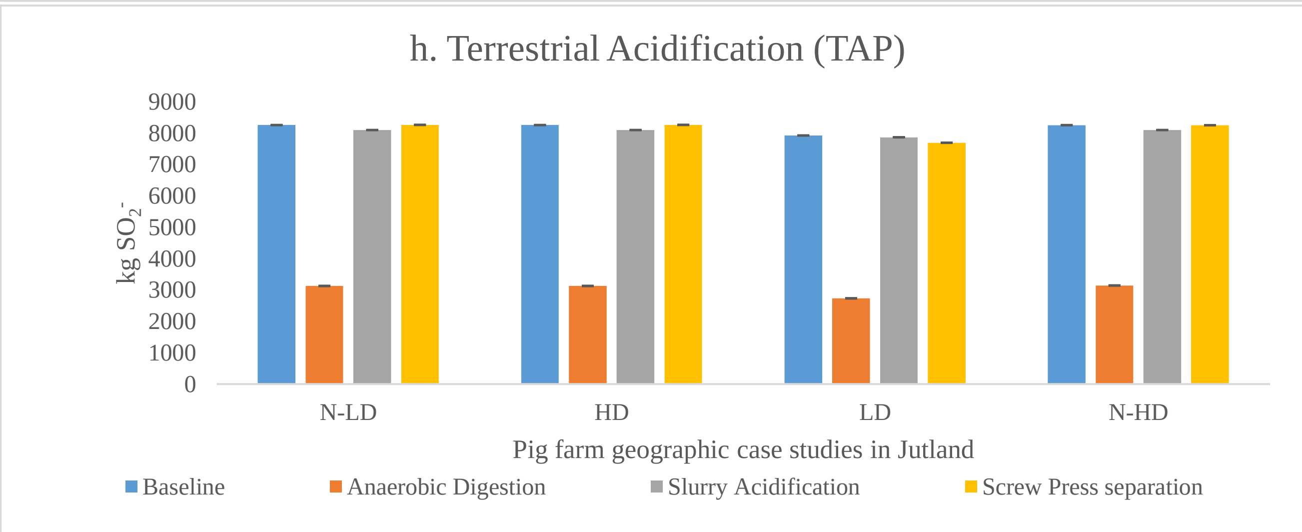


Figure 5.3a-5.3h.: Annual system environmental impact under baseline manure management and with the implementation of three alternative manure management practices (anaerobic digestion, slurry acidification and screw press slurry separation), across four different geographic case studies in Jutland, Denmark. N-LD = Case study less than 400m from Natura 2000 and in region of 2-3 pig farms per hectare. N-HD = Case study less than 400m from Natura 2000 and in region of 7-9 pig farms per hectare. LD = Case study further than 2km from Natura 2000 and in region of 2-3 pig farms per hectare. HD = Case study further than 2km from Natura 2000 and in region of 7-9 pig farms per hectare

5.3.3. *Economic performance and cost-effectiveness of manure management strategies*

Table 5.3 presents the whole-farm annual equivalent value and internal rate of return for all manure management strategies when implemented in the four different geographic location. The findings suggest that farm profitability is largely affected not only by the choice of manure management strategy but also geography. In the N-LD geographic case, anaerobic digestion was 22.2% more profitable (higher annual equivalent value) than the baseline manure management. With the implementation of screw press slurry separation, the farm was 9.05% less profitable and when slurry acidification was implemented the farm performed even worse financially, exhibiting 79.8% lower AEV than the baseline. A similar trend was observed in the N-HD case study, but with the differences greatly enlarged in comparison to N-LD. Specifically, when anaerobic digestion was implemented in N-HD farm profitability was 3.68 times higher than the baseline scenario in this location. In the same geographic case study, screw press separation and slurry acidification performed worse than the baseline scenario by 48.2% and 534% respectively. In cases LD and HD, baseline manure management was the most profitable scenario overall. In both those geographic cases, screw press separation performed second best resulting in 5.65% lower whole-farm annual equivalent value than the baseline. With the implementation of anaerobic digestion in LD farm profitability was 10.3% lower than the baseline manure management scenario and 16.6% lower when it was implemented in HD. Finally, when slurry acidification was implemented in LD and HD, whole-farm AEV was 52.0% and 60.7% lower than the baseline scenario in each of the geographic cases respectively.

Table 5.3.: Whole-farm Annual Equivalent Value (AEV) and Internal Rate of Return (IRR) under baseline manure management and with the implementation of three alternative manure management strategies across the four geographic case studies. N.A = Not Applicable. N-LD = Case study less than 400m from Natura 2000 and in region of 2-3 pig farms per hectare. N-HD = Case study less than 400m from Natura 2000 and in region of 7-9 pig farms per hectare. LD = Case study further than 2km from Natura 2000 and in region of 2-3 pig farms per hectare. HD = Case study further than 2km from Natura 2000 and in region of 7-9 pig farms per hectare

Farm location	**Baseline**		**Anaerobic Digestion**		**Slurry Acidification**		**Screw Press separation**	
	AEV (€)	**IRR (%)**	**AEV (€)**	**IRR (%)**	**AEV (€)**	**IRR (%)**	**AEV (€)**	**IRR (%)**
N-LD	34,427	6.01	42,073	5.75	6,956	3.50	31,312	5.68
HD	52,793	7.59	44,048	5.88	20,731	4.77	49,811	7.25
LD	52,793	7.59	47,341	6.10	25,322	5.18	49,811	7.25
N-HD	6,878	3.50	32,196	5.10	-29,776	0.271	3,564	3.17

Table 5.4 summarises the cost of abatement associated with mitigation of each impact category by the three alternative manure management strategies across the four geographic locations considered. Anaerobic digestion was the only manure management strategy to increase profits while reducing the system environmental impact for GWP, NRRU, NREU, TAP and AWARE. The cost-effectiveness of anaerobic digestion improved when the strategy was implemented in N-HD compared to other geographic locations. The largest differences were observed between N-HD and HD with cost-effectiveness being 4.55 times higher in the former for GWP, 5.20 times for NRRU, 3.96 times for NREU, 3.91 times for TAP and 3.87 times higher for AWARE. Despite achieving substantial abatement potential for several impacts, both slurry acidification and screw press separation incurred additional costs for the abatement of any impact category assessed. For the common categories they mitigated, screw press separation was overall the more cost-effective option, due to its lower cost of implementation and shorter distance required for manure application when compared to slurry acidification. The cost-effectiveness of both slurry acidification and screw press separation exhibited large geographic variability for the various impact categories they mitigated, which reflects the spatial variability in their abatement potential as well as differences in availability of arable land for manure application between the geographic case studies. Overall, both strategies performed the worst for N-HD. With the implementation of screw press separation, the largest geographic difference was found between N-HD and LD, where the cost of abatement for TAP was 162 times higher in N-HD. Cost of abatement was also higher in N-HD for the mitigation of FEP with the largest difference being 19.3 times higher than in HD, NRRU (33.4% higher than HD, LD), AAP (11.6% higher than HD,LD), MEP (10.9% higher than HD,LD) and NREU (7.09% higher than HD,LD). The largest spatial difference in cost-effectiveness of slurry acidification was observed between LD and N-LD for the mitigation of TAP, where it incurred 1.80 times higher additional costs in LD. For AAP, cost of abatement was higher in N-HD than in HD, LD by 34.9%, and for MEP higher in HD than LD by 17.1%.

Table 5.4.: Cost of abatement of the alternative manure management strategies considered for mitigation of each impact category assessed and across the four geographic case studies, expressed in euro per unit of pollutant abated. Negative (-) costs indicate that profit was generated along with environmental impact abatement. N.A = No Abatement. N-LD = Case study less than 400m from Natura 2000 in region of 2-3 pig farms per hectare. N-LD = Case study less than 400m from Natura 2000 and in region of 2-3 pig farms per hectare. N-HD = Case study less than 400m from Natura 2000 and in region of 7-9 pig farms per hectare. LD = Case study further than 2km from Natura 2000 and in region of 2-3 pig farms per hectare. HD = Case study further than 2km from Natura 2000 and in region of 7-9 pig farms per hectare

Cost of abatement per impact category	**Manure management strategy**	**N-LD**	**HD**	**LD**	**N-HD**
Global Warming Potential (€ / kg CO_2 eq.)	Anaerobic digestion	-0.0939	0.107	0.0670	-0.380
Non-Renewable Resource Use (€ / kg Sb eq.)	Anaerobic digestion	-26,907	+30,775	+19,186	-129,374
	Screw Press separation	+28,242	+27,036	+27,036	+36,066
Non-Renewable Energy Use (€ / MJ)	Anaerobic digestion	-0.00102	+0.00117	+0.000727	-0.00346
	Screw Press separation	+0.00531	+0.00508	+0.00508	+0.00544
Available Water Resources – AWARE (€ / m^3)	Anaerobic digestion	-0.0650	+0.0743	+0.0463	-0.213
Freshwater Eutrophication (€ / kg PO_4^{3-} eq.)	Screw Press separation	+6,822	+1,388	+7,225	+28,229
Marine Eutrophication (€ / kg PO_4^{3-} eq.)	Slurry Acidification	+2,189	+2,554	+2,181	N.A
	Screw Press separation	+13.4	+12.8	+12.8	+14.2
Aquatic Acidification (€ / kg SO_2^- eq.)	Slurry Acidification	+1.52	+1.78	+1.52	+2.05
	Screw Press separation	+0.135	+0.129	+0.129	+0.144
Terrestrial Acidification (€ / kg SO_2^- eq.)	Anaerobic digestion	-1.49	+1.70	+1.05	-4.95
	Slurry Acidification	+173	+202	+484	+236
	Screw Press separation	N.A	N.A	+12.9	+2,111

While profitable overall, on-farm anaerobic digestion is a large investment especially for a medium-size farm (500-sow integrated pig farm) (Nolan et al., 2012; Pexas et al., 2020a). However, it results in large on-farm energy discounts with the generation of electricity and heat from manure. Furthermore, it returns a nutrient enriched digestate with improved fertilising properties that translates to sizeable discounts in synthetic fertiliser use (Nolan et al., 2012; Vega et al., 2014; Cherubini et al., 2015). In geographic cases with limited availability of arable land, additional manure transportation costs incurred due to the increased nutrient load of the digestate compared to untreated manure, may worsen the strategy's economic performance and render it less profitable than other potential manure management options. This effect was observed in geographic case HD, where due to a 3 km increase in manure transportation distance compared to the baseline and slurry separation scenarios, anaerobic digestion performed financially worse than both. In contrast to the expected outcomes based on previous findings (Pexas et al., 2020b), in geographic case LD where manure transportation distance was the same (5 km) for all manure management scenarios, on-farm anaerobic digestion also performed worse than the baseline and slurry separation scenarios, which reveals important effects of manure transportation distance on farm profitability. Overall, anaerobic digestion was less sensitive to changes in manure transportation distance when compared to other manure management scenarios (including the baseline), due to the increased revenues from energy-related and fertiliser-related cost discounts associated with its implementation that acted as counterpoints. Such interactions could explain the geographic variability in cost-effectiveness of the strategy to mitigate various environmental impacts, which is a function of the difference in AEV between the strategy and the baseline. AEV differences between anaerobic digestion and the baseline outweighed the respective differences in environmental impact across all geographic locations. These findings enhance the relevance of even basic spatially explicit information with potential economic implications, such as availability of land for manure application, to be integrated in the assessment of cost-effectiveness for alternative manure management strategies.

Slurry acidification is also a large investment with high capital and operating expenses (Kai et al., 2008; Fangueiro et al., 2015). While this study considered the addition of sulphuric acid as the acidifying agent, it is acknowledged that other substances may be able to achieve comparable mitigation of ammonia emissions at a lower cost (Saue & Tamm, 2018). Due to large ammonia emissions reductions achieved at pig housing and manure storage by this strategy, more land would be required for the nitrogen rich acidified slurry to be applied, therefore increasing manure transportation costs and further reducing farm profitability. According to the analysis, 1 km increase in manure transportation distance incurred ~€4,591 (~€0.70 per m^3 of manure), which could explain the large differences observed in farm profitability and cost-effectiveness between the four geographic case studies considered. The observed spatial variability in cost-effectiveness of this manure management strategy could also be explained by geographic differences in abatement potential across the impact categories it mitigated. For impact categories and in geographic cases where the strategy achieved little abatement potential its cost-effectiveness would be relatively poor, particularly if its economic performance was also poor compared to the baseline (e.g. implementation of slurry acidification in LD geographic case for mitigation of TAP).

Mechanical slurry separation is a common manure management practice in Danish pig farming systems, and screw press is amongst the most popular methods due to its relative low cost of implementation (Pexas et al., 2020a; Ten Hoeve et al., 2014). With slurry separation most of the phosphorus ends up in the less voluminous solid fraction, which allows for better nutrient redistribution at field application and helps keep costs low if slurry exceeds the allowance for phosphorus and needs to be applied at longer distances (Ten Hoeve et al., 2014; F. Udesen, SEGES, personal communication, February 27, 2018). Similar to the case of slurry acidification, geographic variability in the economic performance and cost-effectiveness of screw press separation can be attributed largely to the observed differences in distance required for manure transportation and application. Another factor that contributed to the observed differences in financial performance between screw press separation and the baseline manure management strategy, is the cost of application for the solid fraction of manure using broadcast spreading and rapid incorporation (€2.00 per m^3 of manure). This application method is approximately 25% as expensive as the baseline practice of application with trail-hose tanker (~€1.6 per m^3 of manure) and applies to 37% of the total slurry produced, which corresponds to the extracted solid fraction after separation based on the separation efficiency for this specific technology (Ten Hoeve et al., 2014). While it is recognised that the potential for application of the two fractions in different locations might enhance farm economic performance particularly in areas where arable land is scarce (e.g. N-HD), the study simulated field application regimes based only on land availability and specific Danish regulations. The inclusion of more precise spatially explicit information regarding the location where each fraction is applied, as well as relevant regional policies on nutrient deposition could enhance accuracy when assessing the cost-effectiveness of this strategy.

In addition to the factors considered for the spatially explicit cost-effectiveness analysis presented here, the study acknowledges that agglomeration effects can have a significant impact on the efficiency of a pig farming system, especially when considering the implementation of complex investments such as the manure management strategies evaluated here (Larue et al., 2011; Gaigné, Le Gallo, Larue & Schmitt, 2012). While such effects were not simulated due to lack of sufficient relevant data, it is anticipated that as pig farming density increased so might technical efficiency, knowledge spillovers and potentially the availability of more specialised labour force (Larue et al., 2011). This improved farm efficiency could potentially facilitate the realisation and operation of large investments and counterbalance some of the additional costs incurred in dense areas (i.e. where HD and N-HD were located), enhancing farm profitability overall.

Furthermore, it is acknowledged that near Danish Natura 2000 areas, legislation could enforce ceilings on ammonia emissions associated with animal stables and manure storage that in many cases might hinder the expansion of farming operations and therefore farm profitability (Jacobsen & Ståhl, 2018; Jacobsen et al., 2019). Regional restrictions could alter farmer investment behaviour and shift their priorities from the most cost-effective option, towards technologies that primarily target mitigation of specific emissions in compliance with relevant agri-environmental policies (Sutherland, 2010). Such a case could be that slurry acidification may be prioritised over anaerobic digestion to reduce ammonia emission at pig housing and slurry storage, and allow the business to expand near sensitive habitats avoiding relocation.

5.3.4. Methodological implications and challenges

Within the more focused study of this chapter, it is shown that the incorporation of even relatively limited spatial data in livestock LCA models can significantly alter the outcomes of environmental abatement cost assessments, when evaluating investments that aim to improve sustainability of livestock farms. Without the spatially explicit data, all results would have been identical for the four geographic case studies tested with this farm-level LCA model. While the study presents findings for the case of manure management in Danish pig farming operations, the method applied here would be useful when analysing the cost-effectiveness of on-farm investments for environmental impact abatement across the livestock sector, given the universal need to manage manure and reduce emissions associated with animal production.

The study suggests that there is room for further methodological improvements that can be achieved in exercises that address the cost-effectiveness of alternative manure management strategies in pig production systems. A potential avenue for improvement would be to consider testing the framework in countries (case studies) that exhibit larger topographic and climatic variability across space than Denmark (Larue et al., 2011). Asides from topographic heterogeneity, a broader case study could also be more appropriate for investigating the potential effects of socio-economic factors on system sustainability. While nationwide relevant legislation has been considered in this study, the thesis acknowledges that more regionalised regulations are commonly enforced in countries with great diversity in social and economic factors across their spatial extent (Mishra, El-Osta & Gillespie, 2010).

Reducing uncertainties related to the calculation of specific environmental impact categories by improving the calculation methods and by using detailed, regionalised life cycle inventories, could further enhance the discriminating power of such spatially explicit cost-effectiveness assessments (Bulle et al., 2019). Here, system water footprint (AWARE) was identified as such a problem area, where large variability in the results as evident by the observed standard errors, outweighed potential spatial effects (Fig. 3d).

While the study has accounted for uncertainties inherent in the environmental life cycle assessment inventories and models by following well-established methods (Mackenzie et al., 2015), accounting for uncertainties related to data that describe the system financial performance was not possible. This is a particularly difficult task to undertake in spatially explicit economic performance assessments at farm level (Rosenthal & Strange, 2004). Examples of such uncertainties would be the potential geographic variability in prices for various inputs required for the construction and operation of the pig farming system in different geographic case studies (i.e. feed ingredients, construction material, and wages). Spatial variations in input (output) prices can arise due to differences in supplier (buyer) concentrations and competitive intensity between regions. However, such differences are expected to be more prevalent in large countries, where spatial price variations usually reflect greater transportation distances to suppliers or markets. In the more compact geographic context of the present study, such factors are less consequential, therefore justifying the assumptions of uniformity in prices across the case study locations.

5.3.5. Policy implications

This study highlights the importance of accounting for spatial variability in system environmental impact and economic performance when evaluating the cost-effectiveness of strategies that aim to improve farm sustainability. The framework presented here offers opportunities to stakeholders for potential hotspot identification regarding harmful emission, capital and operating costs as well as revenue streams associated with operation of a farming system. In doing so, it enables farm managers to pinpoint areas of improvement and cost-effective strategies towards a more sustainable system. It is essential that producers evaluate their farming operations through such comprehensive environmental and socio-economic assessments, to fully understand the impacts and potential of their business as well as to guide decision making for their improvement (Hellweg & Canals, 2014; Liao et al., 2020).

The results have broader implications in facilitating policy making about the improved environmental and economic performance of various agricultural sectors and on a broader geographic extent. Important trade-offs were identified between the environmental impact categories considered, that relate so much to the choice of specific mitigation strategy as well as to the geographic location where this strategy would perform most effectively. The study highlighted that more expensive investments were required to mitigate GWP, NRRU and NREU, and that such investments can be justified financially where legislation imposes strict restrictions on nutrient deposition through manure application. Policy makers and other stakeholders that set specific environmental mitigation targets in each agricultural sector can use such information to guide investment strategies and meet their goals (Eory et al., 2018).

5.4. Conclusions

An LCA based spatially explicit, whole-farm, cost-effectiveness assessment framework that addressed the interactions between location-specific factors and potential farm investments that aim to improve pig farming system sustainability was presented. The spatially explicit environmental LCA revealed significant effects of location on system environmental impact. The study further showed a significant effect of location on the cost-effectiveness of all manure management strategies considered in mitigating several types of environmental impact. Anaerobic digestion was the only “win-win” manure management strategy that generated profit while improving system environmental performance for two of the geographic locations tested. Slurry acidification and screw press separation achieved sizeable abatement potential for impacts on ecosystem quality, but incurred large additional costs in any of the geographic case studies considered, particularly when arable land was limited near the pig farm. The observed interactions between the cost-effectiveness of a potential farm investment and different geographic locations highlight the importance to account for spatial variability in environmental and economic impact assessments, and reinforces the motivation to improve on relevant existing datasets by accounting for geographic uncertainties. The methodology has applications beyond the specific case study presented here, demonstrating the potential to integrate basic spatial data within farm-level LCA modelling of livestock systems to facilitate decision making for the choice of investments that aim to improve system sustainability in a cost-effective manner.

Chapter 6. General Discussion

6.1.Summary of contribution to scientific knowledge

Improving the sustainability of livestock systems has been a main global objective of the 21st century and a key challenge for Europe (Steinfeld et al., 2006; European Commission, 2020). Special consideration has been given to the pig production industry due to the increasing popularity of pork meat worldwide, and the many environmental issues associated with the intensification of this sector (FAO, 2108a; 2018b). To achieve such an ambitious and multidimensional goal, the effectiveness of novel solutions to reduce the environmental impact of pig farming systems without negatively impacting system profitability requires investigation. Furthermore, it is important that whenever possible assessments of such solutions are performed through a holistic perspective and using robust models that facilitate the communication of outcomes to stakeholders and policy makers. This thesis aimed to address these fundamental needs through the development of comprehensive, integrated LCA methods for the assessment of whole-farm sustainability, while considering the implementation of potential environmental impact abatement strategies in multiple components of contemporary pig farming systems. While Danish and Swedish pig production systems were selected as cases in point, the methodological implications of the models developed in the individual Chapters of the thesis apply to the broader livestock industry and even in other agricultural sectors.

6.1.1. Environmental performance and impact hotspots of current production systems

In Chapter 2 of the thesis, the environmental impacts of pig housing and manure management were evaluated for multiple impact categories through a whole-farm LCA approach that considered potential interactions between these two system components, addressing an important gap in literature for the sustainability of the pig production sector (Reckmann et al., 2012). Important trade-offs were identified between the different environmental impact categories assessed with the implementation of different manure management strategies. For example, while system environmental performance greatly improved for GWP and NREU with the implementation of anaerobic digestion, it was significantly worse for AP and EP. The improvements in performance were attributed mainly due to large discounts in on-farm energy use from the biogas this process produced, while AP and EP increased because of the application in the fields of a nutrient rich digestate with higher concentrations of nitrogen and phosphorus than in untreated slurry. The study showed that modifications in building characteristics and indoor management practices can also significantly affect the environmental performance of the pig production system as a whole.

To the best of the author's knowledge, this thesis presents the first case where the effect on system environmental impacts of concurrent modifications in both pig housing and manure management have been evaluated through a life cycle perspective. Through this analysis, potential environmental impact hotspots were identified in the pig housing component that has previously been given little attention in literature, since the majority of LCA studies in pig production focus mainly on feed production (McAuliffe et al., 2016; Mackenzie et al., 2016). The thesis built on existing literature about factors in pig housing that affect harmful emissions, energy consumption and animal performance (Lammers et al., 2010b; Rigolot et al., 2010; Philippe et al., 2011; Wellock et al., 2013; Philippe & Nicks, 2015) and proposed several ways in which a conventional pig housing system can be modified in terms of infrastructure or management practices, to improve system environmental performance. Furthermore, it highlighted the importance of considering potential interactions between system components prior to the implementation of any modification or management practice, since changes in one (e.g. pig housing) can significantly affect the performance of another (e.g. manure management), and consequently that of the entire system. The thesis identified slurry acidification as the most robust manure management strategy, against modifications in pig housing that affect manure composition. The findings revealed the potential for this particular management strategy to be implemented in a broad range of pig farming types and consistently mitigate specific environmental impacts. Aside from the practical importance for farm managers, the specific outcomes of this study have implications for policy making, as they could offer guidance for the establishment of regulations for new pig housing constructions and technologies, system configurations and alternative management practices that target the reduction of specific environmental impacts.

The results of this analysis showed system environmental impact estimates that were slightly higher than previous LCA studies on Danish (Dalgaard et al., 2007; Nguyen et al., 2011), North American (Lammers et al., 2010a; 2010b; Lammers, 2011; Mackenzie et al., 2016), and other European (Cederberg & Flysjö, 2004; Basset-Mens & Van der Werf, 2005; Stephen, 2012; Reckmann, Traulsen & Krieter, 2013; Noya et al., 2017) pig farming systems. The observed differences could be explained by: i) differences in the configuration and operation of systems for the cases of Canada and US, but also for some European countries such as Denmark, France, and the UK ii) potential variability in background data used to describe relevant processes in each study, and iii) the enhanced detail in the modelling of the pig housing and manure management components in this study, which consider detailed background data on all infrastructure and technological equipment. Although the individual Chapters of the thesis provide an overview of the relevant literature to put specific outcomes of this work in perspective, it is not possible to directly compare overall results with previous LCA studies in any meaningful way, due to variability in core elements of the different analyses (i.e. functional unit, system boundaries) and assumptions regarding the production systems (i.e. mortality rates, management practices) they may be using (McAuliffe et al., 2016). The thesis aimed to provide information that is close and if possible comparable to the reported outcomes of past research, and therefore in the development of the LCA framework it followed established guidelines (FAO, 2018b) and best practices according to literature (Guinée, 2002; Reckmann et al., 2012; Mackenzie et al., 2015).

6.1.2. Cost-effectiveness assessment of alternative farm management strategies for improved system sustainability

While mitigating the environmental impact of pig production systems, it is important that agri-environmental policy makers consider the propensities of pig farms for adoption of particular mitigation strategies. In this regard, pig farms as commercial enterprises are less likely to adopt management strategies that negatively impact on their profitability. Although the economic profit was considered in this thesis as the key motive for the implementation of potential abatement measures, it is worth acknowledging the presence of other drivers that may influence adoption decisions / behaviour. Such factors affecting the adoption of innovations in agriculture have been thoroughly investigated for many years. Farmer's perception of potential economic risks, and even the actual benefits associated with farm innovations change over time and across markets, and should be incorporated in future LCA-based cost-effectiveness assessments (Chavas & Nauges, 2020). The thesis addressed this issue in Chapters 3 and 4 by proposing the use of a whole-farm, integrated LCA framework for the assessment of cost-effectiveness of alternative strategies with pollution abatement potential. Implementing on-farm anaerobic digestion was identified as a cost-effective solution for the improvement of system sustainability, as it can significantly reduce system environmental impact for GWP, NREU and NRRU, while also increasing farm profitability. While there is a consensus regarding the many environmental benefits for pig farms arising from the anaerobic digestion of pig slurry (Vega et al., 2014; Cherubini et al., 2015; Pexas et al., 2020a; 2020b), conflicting results have been reported regarding the economic performance of this strategy worldwide (Nolan et al., 2012; Gutierrez, Xia & Murphy, 2016; Lovarelli, Falcone, Orsi & Bacenetti, 2019; Centre for Innovation Excellence in Livestock – CIEL, 2020). As with the case of environmental LCA outputs, when stakeholders attempt to compare the economic performance of such a complex project across different countries or implementation strategies (i.e. individual or collaborative investment), they should consider a plethora of factors and assumptions underlying the economic impact assessment (Lyng, Skovsgaard, Jacobsen & Hanssen, 2019; Bhatt & Tao, 2020). Electricity tariffs, investment support schemes, specific agri-environmental policy goals and other regulatory conditions that might differ between countries or case studies, can greatly affect the cost-effectiveness of anaerobic digestion (McAuliffe et al., 2017; Lyng et al., 2019; Pexas et al., 2020b). While the whole-farm LCA based framework presented in this thesis provides a robust method to compare the cost-effectiveness of different investment scenarios, system boundaries could be expanded beyond the farm, adopting the approach of a social CBA that considers external costs. In doing so however, important challenges in the valuation of externalities should be addressed. Although this would enable more accurate assessments and reliable comparisons between case studies, which is important in facilitating policy making about investments that aim to improve the sustainability of any agricultural sector, it would be an onerous research task and a potential thesis in its own right.

Chapter 3 adapted a method to present the environmental and economic outcomes of complex LCA models, within a single score for each of several impact categories assessed. It investigated for the first time, the effectiveness of Environmental Abatement Cost (EAC) curves in identifying cost-effective solutions at a farm level and specific to the pig production sector. In this way, the thesis expanded on previous research that has recognised the potential for Marginal Abatement Cost analysis to aid decision making and the prioritisation of pollution mitigation strategies in agriculture (Beaumont & Tinch, 2004; Kesicki & Strachan, 2011; Eory et al., 2013; Pellerin et al., 2017). In addition to evaluating the cost-effectiveness of specific investments, the thesis highlighted the usefulness of the presented method in identifying important trade-offs, not only between the different environmental impacts assessed, but also between the environmental and economic aspects of sustainability. For example, stakeholders can see from a single EAC curve that while larger abatement potential can be achieved for GWP by improving barn insulation than ventilation system efficiency, the latter is more cost-effective per unit of pollutant reduced. The integrated, LCA-based environmental and economic impact assessment framework developed in Chapter 3, can potentially be applied in a broad range of pig production systems, locations and in wider agricultural sectors to provide useful and easy to interpret information for policy makers who aim to identify sustainable solutions to mitigate environmental pollution. Farm managers in other livestock sectors, such as broiler production, dairy cows and beef cattle, could benefit from using the framework presented in this thesis when deciding for the adoption of technological innovations to improve system sustainability. Because the housing component was in the core focus of this thesis, well-established climate control models and an extensive life cycle inventory of commercial construction materials were described that can be used with little adaptation to evaluate the environmental and economic performance of novel designs in buildings of various purposes even outside of agriculture (e.g. residents, offices) (Means & Guggemos, 2015). Chapter 4 demonstrated the adaptability of the framework by applying it to a Swedish pig fattening unit, while Chapter 5 demonstrated its potential to evaluate the cost-effectiveness of one or more investments applied in different locations.

6.1.3. Integrating life cycle based cost-effectiveness assessment tools with climate change and geospatial scenarios

Integration with scenarios on projected climate change

While temperature increase caused by climate change is an important threat to the performance of intensive livestock production systems (Hristov et al., 2018; Mikovits et al., 2019), its effect on pig farm investments that aim to reduce specific harmful emissions and improve animal welfare has been investigated by only a few studies (Valiño et al., 2010; Schauberger et al., 2019). Chapter 4 addressed the issue of cost-effectiveness of farm investments under the changing climate and did so in the context of whole-farm sustainability, an approach that had not been adopted in the past in the pig production sector. The methodological framework and results of this study make a contribution to scientific knowledge and research that aims to increase the resilience of pig production systems by identifying solutions that improve system environmental impact and are robust to future climate change (Smith & Olesen, 2010). As mentioned previously, the methods presented here could be transferred beyond pig production, to help planning for climate change resilience of commercial buildings (Roux, Schalbart, Assoumou & Peuportier, 2016) or even identify trade-offs in solutions for climate change mitigation at an urban landscape level (Xu et al., 2019).

Additionally, through the specific limitations acknowledged in the development of this framework, the thesis identified the lack of primary data when modelling pig cooling technologies under different climatic conditions, as well as the need for more detailed and accurate animal growth and behaviour models to effectively capture their interaction with the changing outdoor and indoor climate. In the assessment of such complicated, multidisciplinary issues it is important that the methods of choice are easy to use and interpret by policy makers and other stakeholders (Howden et al., 2007). These attributes were considered as key elements in the design of the framework presented in Chapter 4, which also used a single metric to summarise environmental and economic outputs for farm investments despite incorporating additional information with the projected climate change scenarios.

Chapter 4 also evaluated system water footprint which is an important but not often studied impact category in the pig production sector as relevant guidelines for its assessment were established only recently (FAO, 2018c). As the water footprint is relatively uncharted territory in LCA based environmental impact assessments, the choice of appropriate water footprint indicators has been a topic of debate among research authorities in recent years (Hoekstra, 2017; Pfister et al., 2017). The thesis selected the most recently established and accepted method to assess water footprint of pig farming systems (Boulay et al., 2018), also adhering to relevant FAO guidelines (FAO, 2018c). In choosing this method, the thesis acknowledged that on-going research aims to further improve its accuracy by addressing the high uncertainties related to the specific models and data inputs (Gil, Bojacá & Schrevens, 2017; Pfister et al., 2017; De Girolamo, Miscioscia, Politi & Barca, 2019; Raffn et al., 2019), and by developing spatially explicit characterisation factors to account for the highly regionalised nature of this impact (Ridoutt et al., 2016; Bulle et al., 2019; Boulay & Lenoir, 2020).

Spatially explicit, LCA-based cost-effectiveness assessment framework

In Chapter 5, the thesis further developed the cost-effectiveness assessment framework with the integration of spatially explicit information to evaluate the environmental and economic performance of environmental abatement strategies in different locations, and for site-dependent environmental impacts such as the water footprint discussed above. While the spatially explicit framework presented in Chapter 5 did not account for climatic variability due to relative homogeneity between the different locations for the particular case study (all in Denmark), the thesis has previously demonstrated the potential for the specific modelling approach to accommodate such climatic scenarios (Chapter 4). Past research has highlighted the importance to evaluate certain environmental impacts through regionalised assessments (Basset-Mens et al., 2006a; Azevedo et al., 2013b; Roy et al., 2014; Henryson et al., 2018), but the need to generate and use spatially explicit information to enhance the LCI and LCIA phases in the design of an LCA framework still remains an issue (Pfister, Oberschelp & Sonderegger, 2020).

The thesis identified a misalignment in the methodological development of spatially explicit LCAs for pig production, where research and big projects (e.g. IMPACT World+ and LC-IMPACT) have focused on the provision of fine-scale impact assessment models but yielded no evidence for a corresponding increase in data-input quality except in some isolated cases (Raffn et al., 2019). The thesis accounted for topographic variability as an important factor that affects potential environmental and economic impacts associated with the manure management component. While geography could greatly affect system sustainability through a plethora of other processes and factors, such as the choice and price of specific feed ingredients and technologies depending on locality, and agglomeration effects, many of these could not be modelled quantitively with accuracy due to relevant data constraints. Improving the standards of data quality for the development of LCI and GIS methods, would greatly enhance modelling realism and estimate accuracy in future studies.

6.2.Modelling pig farming system sustainability: challenges and limitations

LCA-based sustainability assessment methods become increasingly popular in research that aims to identify solutions to facilitate the sustainable intensification of the pig production sector (Gunnarsson, Arvidsson Segerkvist, Wallgren, Hansson & Sonesson, 2020). Specifically, environmental LCA is the most common method for the evaluation of potential environmental impacts arising from pig production systems (Reckmann et al., 2012), while life cycle costing models are widely used to evaluate pig farm economic performance (Singh et al., 2009). However popular, like most sustainability assessment methods, these too suffer from specific limitations and challenges. In the development of this thesis, the main barriers were identified in relation to:

i) the specific decisions and assumptions required at the early stages of framework design, ii) availability and quality of data for the development of the LCI, and iii) environmental impact characterisation and interpretation of the specific results. The thesis attempted to address such methodological challenges throughout, by using up-to-date, geographically and temporally representative data and information, and established uncertainty and sensitivity analysis methods whenever possible. By integrating climate and spatially explicit information along with an LCA-based environmental abatement cost framework, the thesis provided a novel, comprehensive method that can be applied to a wide range of production sectors and for several types of technological innovations.

6.2.1. LCA framework design

As previously mentioned, a fundamental step in the development of a robust LCA-based sustainability assessment framework is 'phase 1 – definition of goal and scope of the study'. Controversies regarding the definition of system boundaries, the choice of allocation method and functional unit, and the limitations of specialised LCA software have dominated the conversations between LCA experts and practitioners, even in recent years (Weidema & Schmidt, 2010; Mackenzie et al., 2017a; McAuliffe, Takahashi & Lee, 2018; 2020).

Identifying all the processes associated with a production system that have potential implications in its environmental and economic performance is a particularly difficult task, and so defining the system boundaries that encompass them all is seldom a straightforward process (Zamagni, Guinée, Heijungs, Masoni & Raggi, 2012). Inconsistencies in system boundaries characterise many LCA studies and make it difficult to compare their outputs. For example, while some pig production environmental LCAs may consider cradle-to-farm gate boundaries, others may focus only on the pig fattening unit, therefore missing important environmental impact hotspots associated with other production stages e.g. gestation (Reckmann et al., 2012; McAuliffe et al., 2016). To minimise the impact of a poor choice of system boundaries, this thesis opted for a cradle-to-farm gate design throughout, which is the most common choice for LCA studies in pig production. In addition, this allowed for a more thorough and accurate investigation of potential environmental and economic impact hotspots, since all the relevant production stages could be assessed and compared. Furthermore, to enhance accuracy of model estimates particularly when incorporating complex technological systems that may have implications broader than the farm level, system expansion was used to capture relevant processes beyond the cradle-to-farm gate boundaries (Finnveden et al., 2009; Reckmann et al., 2013; Cherubini et al., 2015). In a way, this approach partially mimics the consequential LCA method, and although it does not allow for a full exploration of 'what-if' production scenarios, it avoids dealing with highly uncertain data and assumptions as is often the case in consequential LCA models (Dale & Kim, 2014). System expansion is also the preferred method to avoid issues with co-product allocation, a topic that has been widely discussed in the past (Weidema & Schmidt, 2010; Mackenzie et al., 2017a).

Another decision closely related to system boundaries, is that of the functional unit. The functional unit represents the end-product of all processes within the system boundaries, and therefore when the latter are expanded the suitability of the functional unit might be affected. This needs special consideration in comparative assessments, to ensure that the systems compared are equivalent (Finnveden et al., 2009). One potential way to overcome such limitations is by adopting multi-functional or more than one, functional units, enabling a broader interpretation of the outputs and facilitating 'between-system' and 'between-study' comparisons (Zamagni et al., 2012; McAuliffe et al., 2017). Overall, the presented framework was constructed with consideration to best practices and guidelines for LCA studies on livestock production systems according to literature (Swarr et al., 2011; Reckmann et al., 2012; Hauschild et al., 2013; McAuliffe, Takahashi, & Lee, 2018; FAO, 2018b).

6.2.2. Data limitations and related uncertainties

The agri-food sector is generally characterised by more complex and variable systems compared to most other production sectors (Notarnicola et al., 2017). In the case of pig production, data availability and quality to describe the complex pig farming system is perhaps the most common limitation encountered by LCA practitioners (Reckmann et al., 2012). Past research on the development of LCA methodologies has largely focused on novel methods to address uncertainties related to the data and the model (Guo & Murphy, 2012; Mackenzie et al., 2015; Mendoza Beltran et al., 2018; Scrucca et al., 2020; von Brömssen & Röös, 2020). Such methods are available in the majority of commercial and non-commercial LCA-specialised software including Simapro (PRé Consultants, Amersfoort, The Netherlands), which was largely used for the purposes of this thesis. Despite the plethora of uncertainty analysis tools however, data are still the most widely reported source of uncertainty in LCA studies (Bamber et al., 2020) and there is little evidence of efforts to guide the data collection process and resolve this issue (Raffn et al., 2019). The issue of data related uncertainties becomes particularly relevant in the case of socio-economic modelling, where market competitiveness and commercial sensitivities contribute to a lack of transparency and gaps in available secondary datasets (Liu, Li, Li & Wu, 2016). This thesis has identified this particular limitation in Chapters 3 through 5, specifically highlighting the importance of accounting for geographic and temporal variability in data inputs. Feed ingredient, construction material, and technological equipment prices are particularly hard to source due to the above mentioned reasons. Assumptions are often necessary for several fixed costs, such as rents, insurances, interest rates and depreciation rates, for which data is also scarce and usually confidential. Lack of such data can lead to inaccurate estimates of business financial performance when projected in the future, and poor reliability of comparisons between businesses that are placed in different socio-economic contexts. In Chapter 5, the thesis acknowledges this challenge as a barrier in evaluating agglomeration effects on the technical efficiency and economic performance of pig farms, therefore missing an important element of spatial differentiation in pig farm sustainability. A potential way to overcome this limitation, could be with the establishment of data collection protocols that incentivise good data quality and spatiotemporal representativeness, while utilising the remote, automated, continuous monitoring of key parameters for efficient feeding and animal growth (Wellock et al., 2013; Gaillard, Brossard & Dourmad, 2020), optimal pig housing conditions (Chantziaras et al., 2020) and sustainable manure management (Laurent et al., 2014), to build up-to-date, fine-scale datasets. Such automated monitoring protocols can benefit farm managers by reducing the required amount of time and effort, where they would need to collect such information under current conditions. Paying agencies that monitor cross-compliance with agri-environmental policies, and certification bodies that provide assurances upon inspection of sustainable management practices would also greatly benefit from the existence of readily available, databases of close to real-time information. Good data collection practices could be incentivised at this level, integrated to the existing “carrot and stick” approach adopted when monitoring agricultural practices. At a higher organisational level, policy makers would be able to access up-to-date reports on the conditions of any agri-food sector and update relevant policies in ways that promote farm sustainability and avoid conflicting effects.

6.2.3. Impact categories and sustainability indicators

Despite the well established guidelines for performance of LCA studies, the choice and characterisation of impact categories has been considered as a grey area by LCA practitioners. Debate occurs around which are considered to be the most important categories, should midpoint or endpoint indicators be used and which impact assessment method is more appropriate in each case. These choices involve dealing with high uncertainty of existing methods, subjectivity and bias, and in many cases decisions are largely dictated by the recipient of the specific outputs and not the practitioner (Qin, Cucurachi & Suh, 2020). Therefore, although presented as a separate phase in the design of LCAs, these decisions need to be considered closely with the definition of goal and scope stage.

In Chapters 2 and 3, the thesis adhered to the FAO – LEAP guidelines for environmental impact and water footprint assessment of pig production systems (FAO, 2018b; 2018c). In the individual studies, the choice for specific EICs was based on existing research about potential environmental issues mostly affected by pig production. Acidification of terrestrial ecosystems, eutrophication of freshwater bodies, land use change and depletion of water resources are among the most important of such issues (De Vries & De Boer, 2010; McAuliffe et al., 2016; Ritchie, 2020). Although the thesis did not consider land use change and water footprint in the first two chapters due to data limitations, the framework was further developed to address these impact categories in Chapter 4. For the purposes of the spatial LCA in Chapter 5, the assessment of AP was further separated to assess TAP and AAP, and EP was split further in MEP and FEP. In cases of coarse comparisons between different agricultural sectors or when comparing farms located in topographically similar areas, "higher level" indicators may offer a robust solution for the assessment of their environmental performance. However, for the assessment of farms located in areas of high geomorphological diversity, it is important to differentiate between more specific impact categories (e.g. MEP and FEP) as these can be greatly affected by local climatic (e.g. rainfall, solar irradiance) and topographic factors (e.g. slope, soil porosity), in very different ways (Bulle et al., 2019).

With regard to the economic aspect of sustainability the thesis captured relevant cost and revenue streams throughout pig production, evaluating financial metrics that provide information about whole-farm performance, and facilitate comparisons between different on-farm investment scenarios. In this way, the integrated LCA-based environmental and economic framework of this thesis adds great value to the assessment of solutions for the improved sustainability of various agricultural sectors. The environmental abatement cost analysis and curves presented in Chapter 3 offer an easy to interpret method for policy makers to evaluate the cost-effectiveness of pollution mitigation actions, and to analyse potential trade-offs between different EICs and across different pillars of sustainability. With the further integration of social externalities and of factors that describe investment behaviour, the methods could be used to evaluate key drivers and barriers for the adoption of technological innovations in agriculture.

While the above impact categories cover a large share of the major environmental and economic issues in livestock sustainability, the thesis acknowledges the importance of the social aspect that was not accounted for. The implementation of technological innovations and alternative management practices on farm, such as cooling strategies, novel ventilation systems, improved pen hygiene and others, may have positive effects on animal health and welfare (Silva et al., 2008; Velarde & Dalmau, 2012; Scollo, et al., 2016; Jukan, et al., 2017). On the other hand, some strategies such as slurry acidification, frequent slurry removal and increased indoors maintenance that may require intensification of on-farm activities could have adverse effects on animal health and farm worker behaviour (Borst, 2001; Saue & Tamm, 2018). To date, there is a great lack of Social LCAs to consider such effects in the pig production sector (Zira, Röös, Ivarsson, Hoffmann & Rydhmer, 2020). Social LCA models can further capture social perception of product quality and incorporate evaluation methods for unquantifiable impacts on society and animal welfare, that can reveal great potential for the improvement of system sustainability (Weidema, 2006; Grunert, Sonntag, Glanz-Chanos & Forum, 2018; Jawad, Jaber & Nuwayhid, 2018; Scherer, Tomasik, Rueda & Pfister, 2018a). Important lessons can be learned from studies that have implemented such methods in other livestock sectors, for example in broiler production (Tallentire, Edwards, Van Limbergen & Kyriazakis, 2019) or dairy cows (Chen & Holden, 2016).

However, even in cases where all three sustainability aspects can be thoroughly evaluated, the practitioner would need to deal with another barrier concerning the clear communication and interpretation of the results. Aggregating between several impact categories to facilitate communication of outputs within a single sustainability pillar has been a major topic of debates in literature (Bengtsson & Steen, 2000), and identifying suitable single-score indicators to cover two or all aspects of sustainability still presents researchers with a major challenge (Andreas, Serenella, & Jungbluth, 2020; Saad, Nazzal & Darras, 2020). In cases where the models are developed and used primarily to guide decision making, such confusion could be avoided if the decision support systems are co-designed along with various stakeholders, even from the early stages of conceptualisation. Farm managers, policy makers of relevant agri-environmental schemes and even inspectors from relevant paying agencies and assurance schemes, could identify among the potential stakeholders. Through knowledge sharing with stakeholders, great value could be added in future studies by i) identifying potential impact hotspots and management issues even when they are not directly quantifiable, ii) streamlining the modelling framework to reduce computational time and 'input-output noise', and iii) providing tailored services to enhance interpretation of results (Jakku & Thorburn, 2010; Leitch et al., 2019; Norström et al., 2020). Due to limited time and resources in the current project, stakeholders were not involved in the development of the framework presented beyond the tasks of data provision in certain cases. In order to maintain a pragmatic and objective approach, when reporting the outcomes of the specific analyses the thesis did not assign weights to environmental impact categories, and did not consider either the environmental or economic aspect of sustainability as more important than the other. In this way, the stakeholders are provided with granular indicators of system performance and can apply their own weightings to those indicators in the interpretation of the results for policy making.

6.3. Avenues for future research

6.3.1. Strategic planning for sustainable pig production in Europe, using further improved LCA based methods

In this thesis, the potential of LCA-based assessments to effectively evaluate and disseminate outputs (EAC curves) regarding the environmental and economic aspects of pig production system sustainability at a farm level were demonstrated. The comprehensive models presented here could serve as the backbone for future holistic sustainability assessments that also address relevant social issues and expand the boundaries of the analysis beyond the farm.

The thesis discussed the broader implications that several on-farm, environmental abatement strategies have on farm economics and the surrounding environment, and identified key parameters that need to be considered in future designs for more complete and accurate sustainability estimates. An area of focus that could greatly benefit from further advancement of contemporary sustainability assessments, is that of the anaerobic digestion of pig manure. Although it is widely accepted that as a source of renewable energy this technology can help improve the environmental footprint not only of the farm but also of local communities, identifying the most sustainable methods for its implementation has been a challenging task even for the more elegant of assessment methods (Nolan et al., 2012; Vega et al., 2014; Cherubini et al., 2015). To address such problems, one aspect for future research should focus on further enhancing knowledge and availability of information regarding potential quantitative and qualitative socio-economic impacts associated with different policies and implementation strategies (in the case of anaerobic digestion: on-farm, central facilities managed by farmer unions or local governmental authorities), while accounting for geographic and temporal uncertainties. This would require thoroughly planned data collection efforts to supplement integrated and prospective LCA methods (Raffn et al., 2019; Mendoza Beltran et al., 2020). Another important focus point should be the improvement of current mechanistic models that describe novel technological systems implemented on-farm. Future models should be able to capture interactions between any component of the production chain, and predict the impact of modifications in the technological systems. In this way, model realism and accuracy of predictions can be greatly increased. The case of anaerobic digestion of manure is a popular example that would greatly benefit by such thorough modelling approaches. Due to its complexity, current assessments of anaerobic digestion often result to uncertain estimates that intensify the debate around whether this strategy can effectively be implemented on-farm or other implementation strategies are more appropriate. The effectiveness of anaerobic digestion may partially rely to specifications of other system components that affect manure composition, since this is fed directly to the digester. Therefore, it is important that farm managers and policy makers can consider any potential synergistic effects between various on-farm management strategies and technologies, prior to investing in such complex systems.

Developing advanced sustainability assessments could significantly aid policy makers in shaping effective strategic plans for the configuration of pig production systems and management of the pig production sector as a whole. By accounting for factors that affect farmer investment behaviour together with geographic and temporal uncertainties on key economic drivers, agri-environmental policies and funding support schemes could be tailored to more effectively address farm managers' needs for support in the adoption of technological innovations. At this organisational level it would be interesting for future studies to make use of the holistic methods discussed here, to investigate resilience of pig farming businesses to extreme macro socio-economic scenarios such as the Chinese swine flu outbreak or the Covid-19 pandemic that can cause massive disturbances in the agri-food sector. While consequential LCA models have already been developed to explore similar 'what-if' scenarios (McAuliffe et al., 2016), it is important that future research invests resources in addressing the fundamental gaps and uncertainties identified in this thesis to gain more practical value out of predictive sustainability assessments enhancing their applicability in real life agricultural conditions (Zamagni et al 2012).

6.3.2. Novel solutions for improved system sustainability

Another key avenue for research that aims to improve pig farming system sustainability is the development and testing of novel technologies and precision management strategies for more efficient use of resources and reduction of waste throughout production. A critical aspect of this line for future research is to avoid spending valuable resources in the development of solutions that may be beneficial for one pillar of sustainability (e.g. mitigating environmental pollution) but have detrimental effects for another (e.g. extremely high costs of implementation). A major challenge in designing coherent agri-environmental policies without conflicting effects, is the understanding of the inherent trade-offs (Herrero, Thornton, Gerber & Reid, 2009). Trade-offs between different environmental impacts were identified in this thesis, where proposed solutions to mitigate specific emissions led to the potential intensification of other environmental issues. The thesis highlighted such trade-offs for anaerobic digestion, where great reductions were achieved for NREU and GWP when this strategy was implemented, but significant increases were also reported for AP and EP. This is a particularly interesting case and a great example for the challenges encountered in policy making, considering that several nations like Denmark aim to increase adoption of anaerobic digestion to meet their renewable energy use targets, while at the same time they need to address important issues related to their extensive Nitrogen and Phosphorus Vulnerable Zones. Besides between-EI trade-offs, it is imperative that all sustainability pillars are considered equally when shaping cogent policies. This is vital also for the case of technological innovations for improved farm sustainability, from their conceptualisation, to production and testing. Many emerging technologies significantly improve farm environmental performance, but may incur large costs in doing so. Moreover, they may adversely affect animal welfare and even human health (e.g. the case of slurry acidification in pig housing). Low animal welfare standards in their turn can affect product acceptability and therefore lead to reduced profits and impaired financial performance for the business (Busch & Spiller, 2018). When evaluating the effectiveness of an action to improve farm sustainability holistically, the assessment framework and policy makers should consider such important trade-offs between the environmental and socio-economic aspects (Scherer et al., 2018b).

The thesis has also highlighted the importance that when proposed solutions are tested prior to their implementation, potential interactions with all components of the production system should be considered. The establishment of such ‘good practices’ in the development of farming technological innovations and detailed reporting of information on specific technological efficiencies, costs, lifetimes and other relevant parameters, could dramatically increase accuracy of future farm sustainability assessments. Through the specific outcomes of the individual chapters, the thesis identified several areas for improvement of system sustainability. While acknowledging the potential to improve system efficiency by modifying key parameters in the breeding (Ottosen et al., 2020) and feed production components (Mackenzie et al., 2016; Garcia-Launay et al., 2018; Gaillard et al., 2020), this thesis focused on identifying environmental and economic impact hotspots related to pig housing and manure management. The specific findings showed that modifications in pig housing can significantly affect manure composition and the environmental performance of manure management systems. Livestock manure management is associated with approximately 22% of the total emissions arising from European food supply chains in general, and so further investigating solutions that improve this components performance is critical for a more sustainable agriculture (Dennehy et al., 2017; Ritchie, 2020). Increasing the lifetime of technological equipment involved in these system components (e.g. ventilation system, slurry pumping system) and minimising their maintenance requirements, could be a target for future research that will greatly benefit pig farming systems by reducing reinvestment and operational costs, while also reducing resource use for the production of new pieces of equipment. The efficiency of ventilation system and spatial pattern of indoor temperatures have been identified as key factors in reducing harmful emissions that aside from their direct environmental implications could lead to impaired animal growth and welfare. While considerable research efforts have been put into the development of smart climate control and animal monitoring systems, further investigation and generation of primary data regarding the environmental and economic consequences of their implementation is needed (Hoste, Suh & Kortstee, 2017; Jukan, Masip-Bruin, & Amla, 2017; Gautam, Rong, Zhang & Bjerg, 2020).

6.4. Concluding remarks

A key sustainability challenge of our century is to mitigate environmental pollution arising from livestock systems, while increasing production to meet the food needs of the growing global human population. This thesis contributes to scientific knowledge that aims to address this ambitious sustainability goal, through a number of steps that focused on the development of comprehensive LCA-based assessment methods to effectively evaluate potential environmental and economic impacts associated with the operation of pig production systems. Through the more focused case study of European pig production, broader implications for the sustainability of the agri-food sector were identified and discussed. In the individual chapters, novel methodological improvements are presented that highlight i) the importance of careful consideration of all system components and their interactions in environmental LCAs of production chains (Chapter 2), ii) the effectiveness of LCA environmental abatement cost analysis to identify cost-effective solutions for improved system environmental performance, and to communicate that information to policy makers (Chapters 3 and 4), and iii) the importance of accounting for spatial and climatic variability in LCA based sustainability assessments, with the integration of GIS modelling methods and information, and of scenarios on projected climate change (Chapters 4 and 5). The methodological framework described provide a starting point for the advancement of LCA-based sustainability methods, which be implemented in a wide variety of agri-food sectors. Future LCA practitioners review the presented gaps in knowledge and data to focus on the generation of primary data, enhance data collection protocols, and develop novel uncertainty analysis methods, particularly from a socio-economic LCA perspective. The thesis opens up areas in the pig production sector where farm managers can invest and unlock potential benefits for system environmental and economic performance. Technological system developers can focus on the production of innovative solutions targeted to specific environmental impact hotspots and considering sustainability trade-offs, as identified in this thesis. The specific findings can also be used by policy makers to inform “higher-level” decisions for future strategic planning of mitigation actions in agriculture.

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Appendix

Description of the production stages and the baseline scenario.
Gestation stage

To describe the gestation stage we used data provided by the Danish Pig Research Centre (SEGES) (2012) and F. Udesen (personal communications, SEGES, 27 February 2018). We modelled the gestating sow at 3rd to 4th parity (3.5 average number of parities in a sow's life). The gestation period started after the sow had mated. The animal entered this stage at an average of 230.5 kg and finished at a weight of 293.5 kg (average gain of 60 kg). The average daily gain (ADG) was assumed at 0.543 kg and daily feed intake (DFI) at 2.40 kg. Feed intake per sow for the entire stage was 278.4 kg; Table A.1 contains the specific diet composition. The duration of this stage was 116 days. Mortality rate for the gestating sow after birth was 2% and the annual culling rate was 50%.

Four weeks after the mating and up to 7 days before the expected farrowing, the sows were housed in a loose system. They were kept in small groups (40 sows per group) and in pens where they were allocated an average of 2.25 m^2 per sow. In the pens there were feeding stalls (feeding / resting crates) similar to that of the number of animals in the group. The sows had free access to these stalls, which closed behind them to ensure they were protected from other sows while they ate.

Permanent, unlimited access to fresh water was provided as dictated by the European Order on Protection of Pigs. Bite valves supplied an average of 0.65 litres of water per minute (0.5 – 0.8 litres), at 2 to 2.5 atm. There was one bite valve for each feeding crate. On a daily basis, a sow in gestation required an average of 6.5 litres of drinking water (5 – 8 litres).

The stocking density in a loose housing system was 2.25 m^2. That resulted to a 90 m^2 pen where the animals could move freely, assuming 40 sows per pen. A feeding / resting crate for this system occupied 1.365 m^2 and there were as many crates as the individuals in the pen; therefore, 54.6 m^2 of space for that purpose. The total average pen surface was 144.6 m^2. Half of the floor was solid; the other half partly slatted. The thickness of the floor was 10cm. The pens had a T-shape layout, which helped separate the lying and dunging / activity areas. The activity area was 1.2 m wide, so that the animals could move easily in the pen. The pen walls were 1 m high and the thickness of them was 10 cm. The material used for the floor and the penning was concrete. In a partially insulated building, an average of 350 kg of straw was used as bedding per pen per year

(300 – 400 kg). In good insulated buildings, that amount was reduced to an average of 75 kg (70 – 80 kg).

Floor heating was not considered for the gestating stage. The temperature ranged for gestating sows between 16 °C and 18 °C. A low pressure ventilation system was used to control and regulate the temperature, humidity and air velocity.

The solid part of the floor was scratched clean two to three times per week.

Resources for the sow growth and barn (inputs) as well as emissions from this stage, were distributed over the number of live born piglets per litter (14), since this was the main product from the gestation stage.

Farrowing stage

Seven days before the expected farrowing, the pregnant (gestating) sows were moved into farrowing pens where they delivered the piglets. The duration of the farrowing and lactation period was 31 days. Five days after they weaned the piglets, the sows reached heat again. We described this stage with data provided by SEGES (2017) and F. Udesen (personal communications, SEGES, 27 February 2018).

The lactating sow entered the stage at a weight of 247 kg and over the lactation period lost 4 kg: 243 kg ending weight. The feed intake for the lactating sow in this stage was 195.3 kg (diet composition in Table A.1). ADG for piglets was assumed at 0.173 kg. Piglets were delivered at an average weight of 1.35 kg. We assumed their diet was entirely based on sow milk until they reached 6.7 kg and moved onto the nursery stage.

In a farrowing pen, we found a lactating sow and an average of 12.3 piglets per sow. The total surface of the pen was 4.86 m^2 (1.8m width * 2.7 m length). In this area we found a 0.9 m wide and 2.1 m long metal farrowing crate. These 1.89 m^2 were allocated to the lactating sow, which was confined to minimize piglet mortality. In the rest 2.97 m^2, the piglets were free and active. An average of 0.9 m2 (out of the 2.97 m^2 available to the piglets) was covered and used as a shelter with higher temperature in the first days of the stage for the piglets to rest. The floor was 2/3 solid and 1/3 slatted (3.26 m^2 solid concrete floor, 1.6 m^2 metal slatted floor). The thickness of the floor was 10 cm. The pen walls were made out of plastic (PVC) and their dimensions were 0.5 m height and 1.7 cm thickness.

Heating lamps operated over the shelter at a constant rate for an average of 4 days (first 3 to 5 days) in the beginning of the farrowing stage. The output temperature was 35 °C, set to facilitate piglet growth. Room temperature was set for the lactating sow at 17 °C (16 – 18 °C). Underfloor heating operated constantly throughout the entire stage to maintain stable temperature in the room. The combi-diffuse ventilation system worked at 50 % of its capacity, controlling temperature and humidity levels.

Resources for the sow growth and barn (inputs) as well as emissions from the farrowing stage, were distributed over the number of live piglets per sow (12.3), as this production stage mainly delivers piglets at 6.7 kg.

Nursery stage

When the piglets were around 4 weeks old and weighed 6.7 kg, they were moved to the nursery where they grew until 30 kg (~ 11 weeks old). The duration of the nursery stage was 49 days. Two different diets were used for this stage (Table A.1). ADG for the early nursery was 0.296 kg and DFI 0.603 kg, while for the nursery ADG was 0.714 kg and DFI 1.25 kg. We described this stage with data provided by SEGES (2011b) and F. Udesen (personal communications, SEGES, 27 February 2018).

Each pen of the nursery barn had an average of 30 pigs (25 – 35). The stocking density was in accordance with the European Order on the Protection of Pigs, 0.175 m^2 for the 6.7 to 15 kg pigs, and 0.3 m^2 for the 15 to 30 kg pigs. The barn had equal pens with an average pen surface of 9 m^2. The thickness of the floor was 10cm. Half of the floor was solid; the other half partly slatted. The pens were built in a 2:1 length to width ratio (~4.2m * 2.1m) and they had 0.8m high pen walls. The thickness of the walls was 1.7 cm. The materials used for the floor and the penning were concrete and plastic (PVC) respectively.

Floor heating accommodated in the solid part of the floor, operated at a constant rate for the first two weeks (14 days) of the nursery stage. The floor heating system consisted of hot water pipes fed by a boiler.

The lighting system in the barn used 6 double-fluorescent light lamps, of which 3 operated during the day (12 hours) and they were all off during night (12 hours).

The water supply per pig was approximately 0.5 to 1 litre.

The cleaning of the nursery barn took place once for every batch and lasted approximately 3 hours. Water, soap (i.e. MS Foam KL) and disinfectant (i.e. MS Kiemkill) were used. A power cleaner sprayed water for 1.5 hours at a rate of 21 litres per minute. One portable heater (motor size 30 kW) operated for 14 to 16 hours (overnight), set at 30 °C temperature, to dry the barn; the heater consumed an average of 45 litres of diesel for this process (40 to 50 litres). When the outside temperature was above 21 °C (summer period), the amount of diesel consumed to dry the barn after cleaning, was reduced by 30 %; 31.5 litres of diesel were used as an average by the heater.

Growing / Finishing stage

The final production stage was the grower / finisher, which we described with data provided by SEGES (2011a) and F. Udesen (personal communications, SEGES, 27 February 2018). The pigs entered this stage at 30 kg and finished at slaughterweight - 110 kg. The feeding strategy was phase feeding for this stage too (Table A.1). ADG for the growing stage was 0.833 kg and DFI 2.12 kg, while for the finishing stage ADG was 1.07 kg and DFI 2.73. The duration of the growing / finishing stage was 84 days (42 days for growing and 42 days for finishing).

Each pen in the growing / finishing barn had an average of 19 pigs per pen (17 – 21). The stocking density was 0.7 m^2 for growers and finishers. We calculated the average pen surface at 13.3 m^2. The thickness of the floor was 10cm. Half of the floor was solid; the other half partly slatted. The pens had 1m high pen walls. The thickness of the walls was 1.7 cm. The materials used for the floor and the penning were concrete and plastic (PVC) respectively.

The lighting system in the barn used 6 double-fluorescent light lamps, of which 3 operated during the day (12 hours) and they were all off during night (12 hours).

The water supply per pig was approximately 0.5 to 1 litre.

The cleaning of the growing / finishing barn happened once for every batch and lasted around seven hours. Water, soap (i.e. MS Foam KL) and disinfectant (i.e. MS Kiemkill) were used. A power cleaner sprayed water for 3 hours at a rate of 21 litres per minute. Two portable heaters (motor size 30 kW) operated for 14 to 16 hours (overnight), set at 30 °C temperature, to dry the barn; the heaters, combined, consumed an average of 90 litres of diesel for this process (80 to 100 litres). When the outside temperature was above 21 °C (summer period), the amount of diesel consumed to dry the barn after cleaning, was reduced by 30 %; 63 litres of diesel were used as an average by the heaters.

Gilt production stage

For the production of replacement gilts, we assumed the same diet and pig housing conditions as the finishers (slaughterpigs). ADG for the gilts was assumed at 0.589 kg and DFI at 1.78 kg. The duration of this stage, 56 days, differed from the growing / finishing. Furthermore, we considered only a fourth of the barn (250 places, same as gilts produced per year).

Table A2.1: Diet compositions used across all production stages, formulated according to Tybrik et al. (2016) and presented as the contribution of ingredients per 100kg of feed. Quantities were adapted according to Tybirk (personal communications, February 2018).

Feed Ingredients	Gestating sow	Lactating sow	Early nursery weaner	Nursery weaner	Grower	Finisher
Barley	30.0	35.0	20.2	20.0	25.0	26.7
Wheat	25.0	28.7	30.0	26.0	34.7	30.0
Maize	20.0	15.0	19.1	20.0	15.0	20.0
Wheat bran	10.0	1.00	-	-	2.50	5.00
Sunflower meal	3.50	3.00	-	-	4.75	4.50
Whey powder (acid)	-	-	1.00	-	-	-
Palm oil	3.00	2.00	3.00	2.00	1.10	1.00
Sugar beet molasses	2.00	1.00	1.00	1.00	1.00	1.00
Soybean meal	-	8.80	13.3	19.9	8.00	4.30
Soy protein concentrate	-	-	3.25	-	-	-
Potato protein concentrate	-	-	2.60	1.70	-	-
Fishmeal	-	-	2.40	-	-	-
Rapeseed meal	3.50	2.00	-	5.50	4.70	4.50
Monocalcium phosphate (MCP)	0.200	0.790	1.10	0.900	0.550	0.500
Limestone	1.35	1.67	1.60	1.74	1.44	1.30
Salt	0.400	0.400	0.400	0.400	0.400	0.400

L-lysine HCL 98.5	0.140	0.310	0.460	0.400	0.440	0.420
DL-Methionine 99	-	0.0300	0.130	0.110	0.0400	0.0200
Threonine 98.5	0.0200	0.0800	0.150	0.100	0.150	0.130
Tryptophan 98	-	-	0.0400	0.0300	0.0100	0.0200
Vitamins & Minerals	0.880	0.210	0.250	0.200	0.200	0.200
Phytase	0.0100	0.0100	0.0200	0.0200	0.0200	0.0100
TOTAL FEED INTAKE (kg)	278.	195.	16.9	26.3	89.2	115.
DAILY FEED INTAKE (kg)	2.40	6.29	0.603	1.25	2.12	2.73
AVERAGE DAILY GAIN (kg)	0.543	0.173 (suckling piglet)	0.296	0.714	0.833	1.07

Table A2.2: Nutrient characteristics per kg of feed for the different diet formulations. Calculated according to Sauvant et al. (2002). N = Nitrogen, P = Phosphorus, K = Potassium.

Nutrient Characteristic	Gestating sow	Lactating sow	Early nursery	Nursery	Grower	Finisher
Gross Energy (MJ/kg feed)	16.4	16.2	16.5	16.9	16.0	16.1
Dry Matter (g/kg feed)	0.822	0.823	0.821	0.820	0.834	0.837
Crude Protein (g/kg feed)	0.123	0.148	0.193	0.197	0.160	0.145
Crude Fibre (g/kg feed)	0.0459	0.0421	0.0317	0.0395	0.0472	0.0471
Ash Content (g/kg feed)	0.0255	0.0254	0.0309	0.0297	0.0277	0.0263
P Content (g/kg feed)	0.00416	0.00376	0.00414	0.00402	0.00421	0.00421
K Content (g/kg feed)	0.00624	0.00658	0.00764	0.00816	0.00701	0.00650
N Content (g/kg feed)	0.0197	0.0237	0.0309	0.0315	0.0256	0.0231

Table A2.3: Nutrient retention rates for the different production stages according to Sommer et al. (2006). Values presented in gram of nutrient per kilogram of body weight.

Developmental Stage	Nitrogen (g / kg BW)	Phosphorus (g / kg BW)	Potassium (g / kg BW)
Sow under 150 kg	29.7	5.20	2.00
Sow over 150 kg	25.4	5.90	2.00
Weaner from 6.7 to 30 kg	29.3	5.10	2.20
Grower / Finisher from 30 to 110 kg	30.2	5.50	2.20

Table A2.4: Emission factors associated with the various components of the LCA model.

Emission Factor	Value
Methane conversion factor (Ym) for sows (gestation & lactation) (%)	1.00
Methane conversion factor (Ym) for growing pigs (6.7 to 110 kg) (%)	0.390
Energy content of methane (MJ / kg CH_4)	55.6
Total ammoniacal nitrogen (% of total N excreted)	80.0
NH_3 emission factor for partially slatted floor - gestation (% of total NH_3 in manure)	17.0
NH_3 emission factor for partially slatted floor – farrowing (% of total NH_3 in manure)	13.0
NH_3 emission factor for partially slatted floor - nursery (% of total NH_3 in manure)	9.00
NH_3 emission factor for partially slatted floor - growing / finishing (% of total NH_3 in manure)	8.00
N_2 emission factor for partially slatted floor – all production stages (% of total N excreted)	0.200
NO_x emission factor for partially slatted floor – all production stages (% of total N excreted)	0.200
N_2O volatilization factor (% of total N in manure at storage)	1.00
N_2O emission factor – concrete, covered, liquid slurry tank (% of total N in manure at storage)	0.0700
NO_x emission factor – concrete, covered, liquid slurry tank (% of total N in manure at storage)	0.500
Methane conversion factor – concrete, covered, liquid slurry tank (% of total CH_4 from manure)	17.0
Maximum methane producing capacity – B_o (m^3 CH_4 / kg VS)	0.480
NH_3 emission factor – concrete, covered, liquid slurry tank (% of total N in manure at storage)	2.70
NO_x emission factor – all production stages – partially slatted floor (% of total N excreted)	0.200
NH_3 emission factor – field application trail hose tanker (% of total N after storage)	12.4
NO_x emission factor – field application trail hose tanker (% of total N after storage)	0.100
N_2O emission factor – field application trail hose tanker (% of total N after storage)	1.25
NO_3 emission factor – field application trail hose tanker (% of total N after storage)	3.00

NO_3 leaching factor (% of total N after storage)	0.750

Table A2.5: Parameters included in the sensitivity analysis. The minimum and maximum 95% confidence intervals are presented for parameters that followed normal distributions, while minimum and maximum values are presented for parameters with triangular distributions. St. Dev = Standard Deviation, C.I = Confidence Interval

Parameter	Units	Distribution	Mean	St. Dev	Min or -95% C.I	Max or +95% C.I	Data sources
Air refresh rate	Refresh / hour	Normal	1.00	0.0330	0.934	1.07	AHDB (2016)
Air constant	J / kg K	Normal	287.	0.0500	287.	287.	https://www.engineeringtoolbox.com
Barn long side -farrowing	m	Normal	25.0	0.330	24.3	25.7	SEGES (2017)
Barn long side - gestation	m	Normal	44.0	0.660	42.7	45.3	SEGES (2012)
Barn long side - growing / finishing	m	Normal	36.0	0.660	34.7	37.3	SEGES (2011a)
Barn long side - nursery	m	Normal	36.0	0.660	34.7	37.3	SEGES (2011b)
Barn lifetime	Years	Normal	50.0	10.0	30.0	70.0	F. Udesen (personal communication, February 27, 2018)
Barn short side - farrowing	m	Normal	18.0	0.330	17.3	18.7	SEGES (2017)
Barn short side - gestation	m	Normal	25.0	0.660	23.7	26.3	SEGES (2012)
Barn short side - growing / finishing	m	Normal	22.3	0.660	21.0	23.6	SEGES (2011a)
Barn short side - nursery	m	Normal	22.3	0.660	21.0	23.6	SEGES (2011b)
Barn walls' height	m	Normal	2.70	0.200	2.30	3.10	F. Udesen (personal communication, February 27, 2018)

Barn walls' thickness	m	Normal	0.100	0.0100	0.0800	0.120	F. Udesen (personal communication, February 27, 2018)
CH_4 conversion factor - liquid slurry storage	Fraction	Normal	0.170	0.0330	0.104	0.236	Nguyen et al., (2011)
CH_4 emission factor - housing	Fraction	Normal	0.00500	0.000500	0.00400	0.00600	Ten Hoeve et al., (2014)
CH_4 emission factor – storage	Fraction	Normal	0.00800	0.000800	0.00640	0.00960	Ten Hoeve et al., (2014)
Drinking water pump capacity	ltr	Normal	20.8	2.08	16.6	25.0	Lammers et al., (2010)
Drinking water pump efficiency	%	Triangular	0.825	-	0.742	1.00	Lammers et al., (2010)
Drinking water pump motor	kW	Normal	0.370	0.0370	0.296	0.444	Lammers et al., (2010)
Diesel for barn drying (per sq. m) - farrowing	ltr	Normal	0.300	0.0300	0.240	0.360	SEGES (2017)
Diesel for barn drying (per sq. m) - gestation	ltr	Normal	0.300	0.0300	0.240	0.360	SEGES (2012)
Diesel for barn drying - growing / finishing	ltr	Normal	90.0	1.66	86.7	93.3	SEGES (2011a)

Diesel for barn drying - Nursery	ltr	Normal	45.0	1.66	41.7	48.3	SEGES (2011b)
Excavator bucket size	m^3	Triangular	1.19	-	1.00	1.70	K. Myllerup (personal communication, February 27, 2018)
Excavator motor	kW	Triangular	100.	-	92.2	121.	K. Myllerup (personal communication, February 27, 2018)
Ventilation efficiency	m^3 / h W	Normal	20.4	2.03	16.3	24.5	Lammers et al., (2010)
Farrowing crate surface	m^2	Normal	1.90	0.0330	1.83	1.97	SEGES (2017)
Floor thickness, barn	m	Normal	0.100	0.0100	0.0800	0.12	F. Udesen (personal communication, February 27, 2018)
Grader blade width	m	Triangular	5.50	-	3.70	5.50	K. Myllerup (personal communication, February 27, 2018)
Grader motor	kW	Triangular	227.	-	108.	227.	K. Myllerup (personal

							communication, February 27, 2018)
Grader speed 1st gear	m / h	Normal	4,500	450.	3,600	5,400	K. Myllerup (personal communication, February 27, 2018)
Heating lamps operating days - farrowing	Days	Normal	5.00	0.330	4.34	5.66	SEGES (2017)
Heating lamps power	W	Triangular	150.	-	100.	200.	F. Udesen (personal communication, February 27, 2018)
Heater efficiency	%	Triangular	0.980	-	0.880	1.00	Lammers et al., (2010)
Heating system operating days - farrowing	Days	Normal	31.0	0.660	29.7	32.3	SEGES (2017)
Heating system operating days - nursery	Days	Normal	14.0	0.660	12.7	15.3	SEGES (2011b)
Liquid slurry density	kg / m^3	Normal	1,030	11.8	1,000	1,050	Iowa State University
Liquid slurry storage time in days	Days	Triangular	270.	-	180.	365.	F. Udesen (personal communication, February 27, 2018)

N_2 emission factor at housing	Fraction	Normal	0.00200	0.000160	0.00168	0.00232	Dong et al., (2006)
N_2O emission factor at field application	Fraction	Normal	0.0130	0.00125	0.0100	0.0150	Mikkelsen, Albrektsen & Gyldenkærne, (2011)
N_2O emission factor at storage	Fraction	Normal	0.00100	0.0000700	0.000560	0.000840	Dong et al., (2006)
N_2O volatilization factor	Fraction	Normal	0.0100	0.00100	0.00800	0.0120	Nguyen et al., (2011)
NH_3 emission factor at field application	Fraction	Normal	0.124	0.0124	0.0994	0.149	Mikkelsen et al., (2011)
NH_3 emission factor for partially slatted floor - farrowing	Fraction	Normal	0.130	0.0130	0.104	0.156	Mikkelsen et al., (2011)
NH_3 emission factor for partially slatted floor – gestation	Fraction	Normal	0.170	0.0170	0.136	0.204	Mikkelsen et al., (2011)
NH_3 emission factor for partially slatted floor - growing / finishing	Fraction	Normal	0.0800	0.00800	0.0640	0.0960	Mikkelsen et al., (2011)

NH_3 emission factor for partially slatted floor - nursery	Fraction	Normal	0.0900	0.00900	0.0720	0.108	Mikkelsen et al., (2011)
NH_3 emission factor at storage	Fraction	Normal	0.0270	0.00270	0.0216	0.0324	Mikkelsen et al., (2011)
NO_3 emission factor at field application	Fraction	Normal	0.300	0.0300	0.240	0.360	Nguyen et al., (2011)
NO_3 volatilization factor	Fraction	Normal	0.00800	0.000750	0.00600	0.00900	Nguyen et al., (2011)
NO_x emission factor at field application	Fraction	Normal	0.00100	0.000330	0.000340	0.00166	Mikkelsen et al., (2011)
NO_x emission factor at housing	Fraction	Normal	0.00200	0.000200	0.00160	0.00240	Nguyen et al. (2011)
NO_x emission factor at storage	Fraction	Normal	0.00500	0.000330	0.00434	0.00566	Nguyen et al. (2011)
Organic matter degradation rate at housing	Fraction	Normal	0.186	0.0186	0.149	0.223	Ten Hoeve et al. (2015)
Organic matter degradation rate at storage	Fraction	Normal	0.186	0.0186	0.149	0.223	Ten Hoeve et al. (2015)
Pen long side - growing / finishing	m	Normal	4.20	0.0660	4.07	4.33	SEGES (2011a)
Pen long side - nursery	m	Normal	4.20	0.0660	4.07	4.33	SEGES (2011b)

Pen long side - farrowing	m	Normal	2.70	0.0660	2.57	2.83	SEGES (2017)
Pen long side - gestation	m	Normal	14.8	0.0660	14.7	14.9	SEGES (2012)
Pen short side - growing / finishing	m	Normal	2.10	0.0660	1.97	2.23	SEGES (2011a)
Pen short side - nursery	m	Normal	2.10	0.0660	1.97	2.23	SEGES (2011b)
Pen short side - farrowing	m	Normal	1.80	0.0660	1.67	1.93	SEGES (2017)
Pen short side – gestation	m	Normal	7.40	0.0660	7.27	7.53	SEGES (2012)
Pen wall height - farrowing	m	Triangular	0.500	-	0.500	0.700	SEGES (2017)
Pen wall height - gestation	m	Triangular	1.00	-	0.700	1.00	SEGES (2012)
Pen wall height - growing / finishing	m	Triangular	1.00	-	0.700	1.00	SEGES (2011a)
Pen wall height - nursery	m	Triangular	0.500	-	0.500	0.700	SEGES (2011b)
Pen wall thickness - farrowing	m	Normal	0.170	0.0170	0.136	0.204	SEGES (2017)
Pen wall thickness – gestation	m	Normal	0.100	0.0100	0.0800	0.120	SEGES (2012)
Pen wall thickness - growing / finishing	m	Normal	0.170	0.0170	0.136	0.204	SEGES (2011a)
Pen wall thickness - nursery	m	Normal	0.170	0.0170	0.136	0.204	SEGES (2011b)
PO_4 emission factor at field application	Fraction	Normal	0.0200	0.00200	0.0160	0.024	Dong et al., (2006)
Power washer efficiency	%	Triangular	0.917	-	0.825	1.00	Lammers et al., (2010)

Power washer motor	kW	Normal	14.9	1.49	11.9	17.9	Lammers et al., (2010)
Power washer water capacity	ltr	Normal	21.0	0.700	19.6	22.4	F. Udesen (personal communication, February 27, 2018)
Power washing time - growing / finishing	Minutes	Normal	180.	6.00	168.	192.	SEGES (2011a)
Power washing time – nursery	Minutes	Normal	90.0	3.00	84.0	96.0	SEGES (2011b)
Power washing water – farrowing	ltr	Normal	75.0	1.67	71.7	78.3	SEGES (2017)
Power washing water - gestation	ltr	Normal	75.0	1.67	71.7	78.3	SEGES (2012)
Slurry pit depth – farrowing	m	Triangular	0.500	-	0.450	0.570	Kai et al., (2015)
Slurry pit depth – gestation	m	Triangular	0.500	-	0.430	0.530	Kai et al., (2015)
Slurry pit depth – growing / finishing	m	Triangular	0.500	-	0.400	0.600	Kai et al., (2015)
Slurry pit depth – nursery	m	Triangular	0.500	-	0.400	0.570	Kai et al., (2015)
Slurry pit thickness	m	Normal	0.100	0.0100	0.0800	0.120	Kai et al., (2015)
Slurry removal frequency – variation factor on NH_3 emissions	Fraction	Triangular	1.00	-	0.650	1.00	Rigolot et al., (2010)

Slurry surface per pig – growing / finishing	m^2	Triangular	0.290	-	0.150	0.440	Kai et al., (2015)
Slurry surface per sow - farrowing	m^2	Triangular	1.70	-	1.50	2.20	Kai et al., (2015)
Slurry surface per sow - gestation	m^2	Normal	1.50	0.150	1.20	1.80	Kai et al., (2015)
Slurry surface per weaner - nursery	m^2	Triangular	0.120	-	0.100	0.150	Kai et al., (2015)
Specific heat capacity of air	m^2	Normal	0.297	0.0297	0.238	0.35	https://www.engineeringtoolbox.com
Straw for bedding - gestation	kg	Normal	350.	16.7	317.	383.	SEGES (2012)
Total ammoniacal nitrogen (TAN) – Level of slurry dilution	Fraction	Normal	0.705	0.0400	0.625	0.785	Hutchings et al. (2013)
Technological lifetime	Years	Normal	20.0	2.00	16.0	24.0	Lammers et al. (2010)
Temperature – outdoor Denmark	°C	Normal	7.70	2.56	2.58	12.8	F. Udesen (personal communication, February 27, 2018)
Temperature - farrowing	°C	Normal	19.5	0.500	18.5	20.5	SEGES (2017)
Temperature - gestation	°C	Normal	17.0	0.330	16.3	17.7	SEGES (2012)

Temperature - growing / finishing	°C	Normal	17.5	0.830	15.8	19.2	SEGES (2011a)
Temperature - nursery	°C	Normal	20.1	1.05	18.0	22.2	SEGES (2011b)
U value – pig barn	W / m^2 K	Triangular	1.00	-	0.26	4.00	AHDB (2016)

Emission factors associated with alternative manure management scenarios

Table A2.6: Emission factors specific to the alternative manure management scenarios developed (Ten Hoeve, 2015).

Emission Factor	Value
Slurry acidification – slurry at barn pits – NH_3 emission factor (% of total NH_3 in manure)	6.40
Slurry acidification – at storage – NH_3 emission factor (% of total NH_3 in manure)	0.200
Slurry acidification – at field application – NH_3 emission factor (% of total NH_3 in manure)	6.10
Slurry acidification – slurry at barn pits – NO_x emission factor (% of total N excreted)	0.200
Slurry acidification – slurry at barn pits – N_2O emission factor (% of total N excreted)	3.50
Slurry acidification – at field application – N_2O emission factor (% of total N after storage)	3.60
Slurry acidification – slurry at barn pits – NO_3 emission factor (% of total N excreted)	14.8
Separated liquid fraction – at storage – NH_3 emission factor (% of total NH_3 in manure)	1.30
Separated solid fraction – at storage – NH_3 emission factor (% of total NH_3 in manure)	0.300
Separated liquid fraction – at field application – NH_3 emission factor (% of total NH_3 in manure)	12.0
Separated solid fraction – at field application – NH_3 emission factor (% of total NH_3 in manure)	39.0
Separated solid fraction – at storage – N_2O emission factor (% of total N excreted)	0.200
Separated liquid fraction – at field application – N_2O emission factor (% of total N after storage)	2.00
Separated solid fraction – at field application – N_2O emission factor (% of total N after storage)	2.00
Separated solid fraction – at storage – N_2 emission factor (% of total N excreted)	0.400
Separated liquid fraction – at field application – N_2 emission factor (% of total N excreted)	3.80
Separated solid fraction – at field application – N_2 emission factor (% of total N excreted)	3.80
Separated liquid fraction – at field application – NO_3 emission factor (% of total N after storage)	40.5
Separated solid fraction – at field application – NO_3 emission factor (% of total N after storage)	33.2

Anaerobic digestion – at pre-storage – NH_3 emission factor (% of total NH_3 in manure)	1.00
Anaerobic digestion, digestate – at storage – NH_3 emission factor (% of total NH_3 in digestate)	2.00
Anaerobic digestion, digestate – at field application – NH_3 emission factor (% of total NH_3 in digestate)	16.0
Anaerobic digestion, digestate – at field application – N_2O emission factor (% of total N after storage)	2.00
Anaerobic digestion, digestate – at field application – N_2 emission factor (% of total N after storage)	3.50
Anaerobic digestion, digestate – at field application – NO_3 emission factor (% of total N after storage)	36.9

Table A2.7: Sensitivity analysis results for all the parameters assessed. SR = Sensitivity Ratio, NRRU = Non Renewable Resource Use, NREU = Non Renewable Energy Use, GWP = Global Warming Potential, AP = Acidification Potential, EP = Eutrophication Potential

Parameter	Relative SR NRRU	Relative SR NREU	Relative SR GWP	Relative SR AP	Relative SR EP
Air refresh rate	0.0366	0.337	0.115	0.0139	0.00405
Air constant	0.00	0.00	0.00	0.00	0.00
Barn long side -farrowing	0.871	3.80	0.861	0.344	0.123
Barn long side - gestation	0.0585	0.309	0.0622	0.0135	0.00554
Barn long side - growing / finishing	0.181	0.252	0.0999	0.349	0.132
Barn long side - nursery	0.332	2.06	0.469	0.578	0.219
Barn lifetime	5.02	0.508	0.174	0.0609	0.0360
Barn short side - farrowing	0.820	3.64	0.822	0.325	0.116
Barn short side - gestation	0.0554	0.305	0.0605	0.0132	0.00533
Barn short side - growing / finishing	0.168	0.234	0.0924	0.323	0.122
Barn short side - nursery	0.310	1.91	0.436	0.535	0.202
Barn walls' height	0.512	2.01	0.531	0.422	0.157
Barn walls' thickness	0.0885	0.0411	0.0241	0.00468	0.00394
CH_4 conversion factor - liquid slurry storage	0.00	0.00	0.00	0.00	0.00
CH_4 emission factor - housing	0.00	0.00	0.00	0.00	0.00
CH_4 emission factor – storage	0.00	0.00	0.00	0.00	0.00
Drinking water pump capacity	0.00198	0.0878	0.0333	0.00461	0.00134
Drinking water pump efficiency	0.00111	0.0491	0.0187	0.00260	0.000790
Drinking water pump motor	0.00159	0.0703	0.0267	0.00369	0.00108

Diesel for barn drying (per m^2) - farrowing	0.0483	0.765	0.0284	0.0224	0.00747
Diesel for barn drying (per m^2) - gestation	0.0111	0.175	0.00650	0.00511	0.00173
Diesel for barn drying - growing / finishing	0.9647	17.1	0.505	0.365	0.145
Diesel for barn drying - Nursery	0.0331	0.588	0.0174	0.0125	0.00499
Excavator bucket size	0.0364	0.576	0.0214	0.0168	0.00565
Excavator motor	0.0306	0.484	0.0180	0.0141	0.00475
Ventilation efficiency	0.522	23.1	8.78	1.21	0.351
Farrowing crate surface	0.00	0.00	0.00	0.00	0.00
Floor thickness, barn	0.229	0.106	0.0623	0.0121	0.0101
Grader blade width	0.000667	0.0106	0.000390	0.000313	0.000110
Grader motor	0.000451	0.00712	0.000270	0.000206	0.0000689
Grader speed 1st gear	0.000563	0.00890	0.000319	0.000256	0.000108
Heating lamps operating days - farrowing	0.00738	0.327	0.124	0.0172	0.00499
Heating lamps power	0.00738	0.327	0.124	0.0172	0.00498
Heater efficiency	0.958	4.12	0.930	0.0376	0.0150
Heating system operating days - farrowing	0.870	2.53	0.592	0.0263	0.00797
Heating system operating days - nursery	0.182	1.92	0.414	0.0145	0.00820
Liquid slurry density	0.00	0.00	0.00	0.00	0.00
Liquid slurry storage time in days	0.00	0.00	0.00	0.00	0.00
N_2 emission factor at housing	0.0399	0.0140	0.0126	0.000455	0.0708
N_2O emission factor at field application	0.332	0.116	6.61	0.0117	1.24
N_2O emission factor at storage	0.0131	0.00460	0.966	0.000404	0.0483

N_2O volatilization factor	0.0446	0.0157	1.58	0.00124	0.167
NH_3 emission factor at field application	2.63	0.923	1.33	16.5	9.78
NH_3 emission factor for partially slatted floor -farrowing	0.178	0.0625	0.650	1.75	0.649
NH_3 emission factor for partially slatted floor – gestation	0.114	0.0400	0.642	1.12	0.415
NH_3 emission factor for partially slatted floor – growing/finishing	0.523	0.184	0.694	5.15	1.91
NH_3 emission factor for partially slatted floor - nursery	0.229	0.0804	0.657	2.25	0.835
NH_3 emission factor at storage	0.335	0.117	0.662	3.28	1.21
NO_3 emission factor at field application	8.02	2.81	2.43	0.282	31.2
NO_3 volatilization factor	0.0597	0.0209	1.70	0.00210	0.224
NO_x emission factor at field application	0.0268	0.00940	0.197	0.0724	0.0514
NO_x emission factor at housing	0.0403	0.0141	0.630	0.158	0.0407
NO_x emission factor at storage	0.0943	0.0331	0.954	0.370	0.0954
Organic matter degradation rate at housing	0.00	0.00	0.684	0.00	0.00
Organic matter degradation rate at storage	0.00	0.00	0.684	0.00	0.00
Pen long side - growing / finishing	0.00	0.00	2.57	0.00	0.00
Pen long side - nursery	0.00	0.00	14.1	0.00	0.00
Pen long side - farrowing	0.00	0.00	3.99	0.00	0.00
Pen long side - gestation	0.00	0.00	3.99	0.00	0.00
Pen short side - growing / finishing	0.00	0.00	1.71	0.00	0.00
Pen short side - nursery	0.00	0.00	7.03	0.00	0.00
Pen short side - farrowing	0.00	0.00	2.00	0.00	0.00
Pen short side – gestation	0.00	0.00	2.00	0.00	0.00

Pen wall height - farrowing	0.00	0.00	0.314	0.00	0.00
Pen wall height - gestation	0.00000332	0.00	0.418	0.00	0.00
Pen wall height - growing / finishing	0.00	0.00	0.418	0.00	0.00
Pen wall height - nursery	0.00	0.00	0.314	0.00	0.00
Pen wall thickness - farrowing	0.00	0.00	0.627	0.00	0.00
Pen wall thickness – gestation	0.00	0.00	0.627	0.00	0.00
Pen wall thickness - growing / finishing	0.00	0.00	0.627	0.00	0.00
Pen wall thickness - nursery	0.00	0.00	0.627	0.00	0.00
PO4 emission factor at field application	0.00	0.00	0.627	0.00	22.3
Power washer efficiency	0.00825	0.366	1.53	0.0192	0.00551
Power washer motor	0.0109	0.484	0.811	0.0254	0.00737
Power washer water capacity	0.00710	0.466	2.04	0.0243	0.00693
Power washing time - growing / finishing	0.00298	0.0322	1.89	0.00178	0.000650
Power washing time – nursery	0.00154	0.0167	1.89	0.000930	0.000325
Power washing water – farrowing	0.0314	0.362	2.97	0.0199	0.00666
Power washing water - gestation	0.00720	0.0829	2.86	0.00455	0.00162
Slurry pit depth – farrowing	0.00255	0.0403	0.00152	0.00119	0.000413
Slurry pit depth – gestation	0.000565	0.00882	0.000329	0.000269	0.000120
Slurry pit depth – growing / finishing	0.00452	0.0715	0.00266	0.00209	0.000722
Slurry pit depth - nursery	0.00193	0.0305	0.00113	0.000889	0.000309
Slurry pit thickness	0.231	0.137	0.0634	0.0130	0.0104
Slurry removal frequency – variation factor on NH_3 emissions	1.04	0.366	0.133	10.3	3.81

Slurry surface per pig – growing / finishing	0.140	0.287	0.0425	0.0133	0.00776
Slurry surface per sow - farrowing	0.0106	0.130	0.00548	0.00390	0.00137
Slurry surface per sow - gestation	0.0682	0.0591	0.0191	0.00434	0.00321
Slurry surface per weaner - nursery	0.0415	0.114	0.0132	0.00472	0.00251
Specific heat capacity of air	0.00	0.00	0.00	0.00	0.00
Straw for bedding - gestation	0.000827	0.00141	0.000930	0.00127	0.00326
Total ammoniacal nitrogen (TAN) – Level of slurry dilution	5.17	1.85	0.533	40.4	19.1
Technological lifetime	63.5	2.66	1.07	0.400	0.276
Temperature – outdoor Denmark	0.752	3.18	0.690	0.911	0.337
Temperature - farrowing	1.66	4.40	1.15	1.98	0.728
Temperature - gestation	0.0219	3.44	1.30	0.805	0.313
Temperature - growing / finishing	0.529	0.510	0.444	5.15	1.91
Temperature - nursery	0.519	3.48	0.806	2.85	1.06
U value – pig barn	1.18	5.21	1.26	1.36	0.503

Table A2.8: Environmental impacts of the baseline manure management system under baseline and alternative pig housing scenarios. NRRU = Non Renewable Resource Use, NREU = Non Renewable Energy Use, GWP = Global Warming Potential, AP = Acidification Potential, EP = Eutrophication Potential, T = Temperature, NA = not available.

Impact Category		**Average**	**Decreased T**	**Increased T**	**Increased barn insulation**	**Decreased barn insulation**	**Increased slurry dilution**	**Decreased slurry dilution**	**Decreased ventilation efficiency**	**Increased ventilation efficiency**	**Daily slurry removal**
NRRU (kg Sb eq.)[1]	Mean	3.40 E-07	3.37 E-07	3.43 E-07	3.31 E-07	3.74 E-07	3.35 E-07	3.46 E-07	3.46 E-07	3.39 E-07	3.36 E-07
	St.dev	2.19 E-07	2.18 E-07	2.18 E-07	2.18 E-07	2.15 E-07	2.17 E-07	2.16 E-07	2.16 E-07	2.19 E-07	2.17 E-07
	% ≤ baseline	NA	100.	0.00	100.	0.00	100.	0.00	0.00	100.	100.
NREU (MJ)[2]	Mean	17.7	17.6	17.8	17.3	19.4	17.7	17.7	17.7	17.2	17.7
	St.dev	0.691	0.637	0.639	0.642	0.489	0.688	0.689	0.689	0.681	0.689
	% ≤ baseline	NA	100.	0.200	100.	0.00	100.	0.00	0.00	100.	100.
AP (kg SO_2 eq.)[3]	Mean	2.78 E-02	2.75 E-02	2.81 E-02	2.75 E-02	2.86 E-02	2.63 E-02	2.93 E-02	2.93 E-02	2.77 E-02	2.63 E-02
	St.dev	7.60 E-04	7.12 E-04	7.16 E-04	7.06 E-04	6.82 E-04	6.83 E-04	6.68 E-04	6.68 E-04	7.58 E-04	6.44 E-04
	% ≤ baseline	NA	100.	0.00	100.	0.00	100.	0.00	0.00	100.	100.
EP (kg PO_4^{---} eq.)[4]	Mean	2.46 E-02	2.45 E-02	2.46 E-02	2.45 E-02	2.47 E-02	2.43 E-02	2.49 E-02	2.49 E-02	2.46 E-02	2.44 E-02
	St.dev	3.97 E-04	3.90 E-04	3.91 E-04	3.90 E-04	3.86 E-04	3.85 E-04	3.82 E-04	3.82 E-04	3.97 E-04	3.80 E-04
	% ≤ baseline	NA	100.	0.00	100.	0.00	100.	0.00	0.00	100.	100.

[1] Sb = antimony
[2] MJ = megajouls
[3] SO_2 = sulphate
[4] PO_4^{---} = phosphate

GWP (kg CO_2 eq.)[1]	Mean	3.57	3.56	3.58	3.54	3.68	3.57	3.57	3.57	3.52	3.57
	St.dev	5.10 E-02	4.76 E-02	4.77 E-02	4.79 E-02	3.79 E-02	5.08 E-02	5.07 E-02	5.07 E-02	5.00 E-02	5.07 E-02
	% ≤ baseline	NA	100.	0.00	100.	0.00	100.	0.00	0.00	100.	0.00

[1] CO_2 = carbon dioxide

Table A2.9: Environmental impacts of the slurry acidification scenario under baseline and alternative pig housing scenarios. NRRU = Non Renewable Resource Use, NREU = Non Renewable Energy Use, GWP = Global Warming Potential, AP = Acidification Potential, EP = Eutrophication Potential, T = Temperature, NA = not available.

Impact Category		**Average**	**Decreased T**	**Increased T**	**Increased barn insulation**	**Decreased barn insulation**	**Increased slurry dilution**	**Decreased slurry dilution**	**Decreased ventilation efficiency**	**Increased ventilation efficiency**	**Daily slurry removal**
NRRU (kg Sb eq.)[1]	Mean	4.94 E-07	4.92 E-07	4.96 E-07	4.86 E-07	5.27 E-07	4.92 E-07	4.96 E-07	4.95 E-07	4.93 E-07	4.94 E-07
	St.dev	2.28 E-07	2.27 E-07	2.27 E-07	2.27 E-07	2.24 E-07	2.27 E-07	2.27 E-07	2.28 E-07	2.28 E-07	2.28 E-07
	% ≤ baseline	NA	100.	0.00	100.	0.00	100.	0.00	0.00	100.	100.
NREU (MJ)[2]	Mean	18.1	18.0	18.2	17.7	19.7	18.1	18.1	18.6	17.7	18.1
	St.dev	0.696	0.643	0.646	0.651	0.508	0.695	0.695	0.685	0.689	0.696
	% ≤ baseline	NA	100.	0.00	100.	0.00	100.	0.00	0.00	100.	100.
AP (kg SO_2 eq.)[3]	Mean	2.00 E-02	1.99 E-02	2.00 E-02	1.99 E-02	2.01 E-02	1.96 E-02	2.03 E-02	2.00 E-02	1.99 E-02	1.98 E-02
	St.dev	3.03 E-04	2.98 E-04	2.98 E-04	2.97 E-04	2.90 E-04	2.85 E-04	2.83 E-04	3.00 E-04	3.01 E-04	2.93 E-04
	% ≤ baseline	NA	100.	0.00	100.	0.00	100.	0.00	0.00	100.	100.
EP (kg PO_4^{---} eq.)[4]	Mean	2.11 E-02	2.11 E-02	2.11 E-02	2.11 E-02	2.11 E-02	2.10 E-02	2.12 E-02	2.11 E-02	2.11 E-02	2.11 E-02
	St.dev	2.97 E-04	2.96 E-04	2.96 E-04	2.96 E-04	2.95 E-04	2.93 E-04	2.924 E-04	2.96 E-04	2.97 E-04	2.95 E-04
	% ≤ baseline	NA	100.	0.00	100.	0.00	100.	0.00	0.00	100.	100.
GWP (kg CO_2 eq.)[5]	Mean	3.90	3.87	3.88	3.85	3.98	3.87	3.87	3.92	3.84	3.87
	St.dev	5.89 E-02	5.548 E-02	5.57 E-02	5.60 E-02	4.67 E-02	5.89 E-02	5.88 E-02	5.77 E-02	5.82 E-02	5.88 E-02
	% ≤ baseline	NA	99.0	0.500	100.	0.00	71.0	45.5	0.00	100.	0.00

[1] Sb = antimony
[2] MJ = megajouls
[3] SO_2 = sulphate
[4] PO_4^{---} = phosphate
[5] CO_2 = carbon dioxide

Table A2.10: Environmental impacts of the screw press slurry separation scenario under baseline and alternative pig housing scenarios. NRRU = Non Renewable Resource Use, NREU = Non Renewable Energy Use, GWP = Global Warming Potential, AP = Acidification Potential, EP = Eutrophication Potential, T = Temperature, NA = not available.

Impact Category		**Average**	**Decreased T**	**Increased T**	**Increased barn insulation**	**Decreased barn insulation**	**Increased slurry dilution**	**Decreased slurry dilution**	**Decreased ventilation efficiency**	**Increased ventilation efficiency**	**Daily slurry removal**
NRRU (kg Sb eq.)[1]	Mean	4.59 E-07	4.57 E-07	4.61 E-07	4.51 E-07	4.90 E-07	4.54 E-07	4.71 E-07	4.60 E-07	4.58 E-07	4.56 E-07
	St.dev	1.82 E-07	1.86 E-07	1.86 E-07	1.86 E-07	1.84 E-07	1.85 E-07	1.81 E-07	1.87 E-07	1.87 E-07	1.86 E-07
	% ≤ baseline	NA	100.	0.00	100.	0.00	100.	0.00	0.00	100.	100.
NREU (MJ)[2]	Mean	17.3	17.2	17.4	16.9	18.9	17.3	17.4	17.8	17.0	17.3
	St.dev	0.671	0.622	0.624	0.627	0.502	0.668	0.665	0.657	0.662	0.669
	% ≤ baseline	NA	100.	0.00	100.	0.00	100.	0.00	0.00	100.	100.
AP (kg SO_2^- eq.)[3]	Mean	4.52 E-02	4.50 E-02	4.54 E-02	4.50 E-02	4.56 E-02	4.38 E-02	4.82 E-02	4.53 E-02	4.51 E-02	4.44 E-02
	St.dev	1.48 E-03	1.45 E-03	1.45 E-03	1.45 E-03	1.43 E-03	1.40 E-03	1.36 E-03	1.48 E-03	1.48 E-03	1.40 E-03
	% ≤ baseline	NA	100.	0.00	100.	0.00	100.	0.00	0.00	100.	100.
EP (kg PO_4^{3-} eq.)[4]	Mean	2.57 E-02	2.57 E-02	2.58 E-02	2.57 E-02	2.58 E-02	2.55 E-02	2.64 E-02	2.57 E-02	2.57 E-02	2.56 E-02
	St.dev	4.70 E-04	4.66 E-04	4.66 E-04	4.66 E-04	4.62 E-04	4.57 E-04	4.45 E-04	4.70 E-04	4.70 E-04	4.57 E-04
	% ≤ baseline	NA	100.	0.00	100.	0.00	100.	0.00	0.00	100.	100.
GWP (kg CO_2 eq.)[5]	Mean	3.80	3.80	3.80	3.78	3.90	3.80	3.80	3.85	3.77	3.81
	St.dev	5.91 E-02	5.60 E-02	5.62 E-02	5.65 E-02	4.84 E-02	5.88 E-02	5.83 E-02	5.77 E-02	5.82 E-02	5.81 E-02
	% ≤ baseline	NA	97.5	0.00	100	0.00	100.	0.00	0.00	100.	0.00

[1] Sb = antimony
[2] MJ = megajouls
[3] SO_2 = sulphate
[4] PO_4^{---} = phosphate
[5] CO_2 = carbon dioxide

Table A2.11: Environmental impacts of the anaerobic digestion scenario under baseline and alternative pig housing scenarios. NRRU = Non Renewable Resource Use, NREU = Non Renewable Energy Use, GWP = Global Warming Potential, AP = Acidification Potential, EP = Eutrophication Potential, T = Temperature, NA = not available.

Impact Category		**Average**	**Decreased T**	**Increased T**	**Increased barn insulation**	**Decreased barn insulation**	**Increased slurry dilution**	**Decreased slurry dilution**	**Decreased ventilation efficiency**	**Increased ventilation efficiency**	**Daily slurry removal**
NRRU (kg Sb eq.)[1]	Mean	2.25 E-07	2.21 E-07	2.28 E-07	2.15 E-07	2.60 E-07	2.21 E-07	2.28 E-07	2.26 E-07	2.24 E-07	2.17 E-07
	St.dev	2.75 E-07	2.74 E-07	2.74 E-07	2.74 E-07	2.71 E-07	2.74 E-07	2.74 E-07	2.75 E-07	2.75 E-07	2.72 E-07
	% ≤ baseline	NA	100.	0.00	100.	0.00	100.	0.00	0.00	100.	100.
NREU (MJ)[2]	Mean	10.6	10.5	10.7	10.2	12.3	10.6	10.6	11.1	10.3	10.6
	St.dev	0.718	0.667	0.671	0.667	0.536	0.716	0.716	0.707	0.711	0.714
	% ≤ baseline	NA	100.	0.00	100.	0.00	100.	0.00	0.00	100.	100.
AP (kg SO_2^- eq.)[3]	Mean	2.96 E-02	2.93 E-02	2.99 E-02	2.93 E-02	3.03 E-02	2.90 E-02	3.02 E-02	2.97 E-02	2.95 E-02	2.82 E-02
	St.dev	8.23 E-04	7.81 E-04	7.84 E-04	7.73 E-04	7.41 E-04	7.53 E-04	7.54 E-04	8.21 E-04	8.22 E-04	7.00 E-04
	% ≤ baseline	NA	100.	0.00	100.	0.00	100.	0.00	0.00	100.	100.
EP (kg PO_4^{3-} eq.)[4]	Mean	2.66 E-02	2.65 E-02	2.66 E-02	2.65 E-02	2.66 E-02	2.65 E-02	2.66 E-02	2.66 E-02	2.66 E-02	2.64 E-02
	St.dev	4.53 E-04	4.48 E-04	4.49 E-04	4.47 E-04	4.43 E-04	4.45 E-04	4.45 E-04	4.53 E-04	4.53 E-04	4.38 E-04
	% ≤ baseline	NA	100.	0.00	100.	0.00	100.	0.00	0.00	100.	100.
GWP (kg CO_2 eq.)[5]	Mean	3.24	3.23	3.24	3.21	3.34	3.24	3.23	3.29	3.20	3.25
	St.dev	5.81 E-02	5.49 E-02	5.52 E-02	5.50 E-02	4.64 E-02	5.75 E-02	5.75 E-02	5.69 E-02	5.73 E-02	5.70 E-02
	% ≤ baseline	NA	99.0	0.00	100.	0.00	0.00	100.	0.00	100.	0.00

[1] Sb = antimony
[2] MJ = megajouls
[3] SO_2 = sulphate
[4] PO_4^{---} = phosphate
[5] CO_2 = carbon dioxide

Economic model and system description

We calculated capital costs over the time horizon accounting for the working capital (i.e. breeding stock), the pig housing component (i.e. barn-building, climate control equipment, feed & water delivery systems, slurry pumping system) and the manure management component (i.e. slurry tanks, field application equipment). We considered technological reinvestment for components that were expected to require renewal at intervals more frequent than the 25-year time horizon of the study. In addition, we accounted for costs related to the installation and insurance of the capital equipment.

The operational expenses consisted of *animal & pig housing management related* costs (i.e. breeding stock purchase, veterinary and medicine costs, energy, equipment maintenance, labour), *feed & water* and *manure management related* costs (i.e. equipment maintenance, energy & labour for manure treatment including application). The most important miscellaneous costs we considered were the annual maintenance of capital equipment, production rights, insurance over capital equipment and animal stock.

In the calculation of farm revenue streams, we considered the annual production of slaughter pigs and culled sows, as well as discounts in synthetic fertiliser due to the application of slurry. In the case of anaerobic digestion we also accounted for the production of electricity as a source of revenue through discounts in on-farm electricity use.

The following main assumptions were used for the DCF analysis:

i) An inflation-adjusted discount rate of 3% was used to represent the interest rate in Denmark for medium-to-long-term investments.

ii) System productivity (slaughter pigs sold sow^{-1} year^{-1}) and product demand were assumed constant over the time horizon.

iii) Capital costs considered in the DCF included *initial fixed (buildings & technological equipment)* and *working capital (livestock & direct inputs)*, as well as *periodic renewal costs*.

iv) Operating expenses comprised *variable costs (e.g. feed related, on-farm energy)* and *cash overheads (e.g. maintenance, insurance)*.

v) Revenues from the production system included: *sales value per kg of live weight pig sold at slaughter weight*, *sales value per kg of culled sow sold*, *avoided costs for* *synthetic fertiliser – field application of manure* and *electricity & heat production (case of AD).*

The Internal Rate of Return of an investment represents its expected percentage return on capital over the time horizon. It is expressed as the value of discount rate for which the Net Present Value of the investment is equal to zero (eq.1). Comparing the IRR of potential investments is another common method to guide decision making in an enterprise (e.g. pig farm); the higher the IRR of an investment the more desirable it is to undertake. A negative IRR value means that the aggregate amount of cash flows caused by an investment is less than the amount of the initial investment.

In certain cases of comparison between mutually exclusive projects, the NPV and IRR valuation methods might return conflicting results, i.e. an investment might have higher NPV (or AEV) but lower IRR than another potential investment, which can be attributed to differences in the size of investment or timing of cash flows. While both valuation methods are acceptable, we selected projects based on their AEV because this approach uses reinvestment rates closer to the current cost of capital and therefore is more realistic.

The cost of each diet was calculated using the ingredient prices listed in Table A3.1 below.

Table A3.1: Price of feed ingredients used to formulate the different diets. The presented values are weighted averages of data provided by the Danish Pig Research Centre (SEGES) for the 2012 – 2017 period.

Feed ingredient	**Unit**	**€ per unit**
Barley	kg	0.182
DL-Methionine 99	kg	24.9
Fish meal	kg	1.51
Ground calcium carbonate (limestone)	kg	0.102
L-Lysine HCL 98.5	kg	1.56
Maize	kg	0.214
Mineral supplement for pigs 9 – 30kg	kg	1.16
Mineral supplement for pigs 30 – 100kg (incl. sows)	kg	1.16
Monocalcium Phosphate (MCP)	kg	0.652
Palm oil mix	kg	0.782
Potato protein concentrate	kg	1.59

Rapeseed meal	kg	0.269
Salt	kg	1.61
Soymeal	kg	0.401
Soy protein concentrate	kg	0.914
Sugar beet molasses	kg	0.175
Sunflower seed meal	kg	0.253
Threonine 98.5	kg	1.93
Tryptophan 98	kg	12.4
Water	kg	0.00840
Wheat	kg	0.189
Wheat bran	kg	0.126
Whey powder	kg	0.799

Table A3.2: Breakdown of costs associated with the production of 1 kilogram of live weight slaughter pig at 110kg under baseline conditions (Business As Usual) and with each stand-alone abatement measure implemented.

Costs (€)	**Business As Usual**	**Anaerobic Digestion**	**Slurry Acidification**	**Increased Ventilation Efficiency**	**Improved Insulation**	**Frequent Slurry Removal**	**Increased Slurry Dilution**
Animal stock related costs	0.0849	0.0849	0.0849	0.0849	0.0849	0.0849	0.0849
Feed & Water	0.695	0.695	0.695	0.695	0.695	0.695	0.695
Pig housing capital costs	0.0189	0.0189	0.0189	0.0189	0.0192	0.0189	0.0189
Pig housing operating costs – incl. labour	0.167	0.167	0.167	0.161	0.166	0.182	0.169
Manure management capital costs	0.000274	0.000892	0.000347	0.000274	0.000274	0.000274	0.000274
Manure management operating costs – incl. labour	0.0309	0.0644	0.0518	0.0309	0.0309	0.0309	0.0463
Miscellaneous	0.0661	0.0661	0.0661	0.0725	0.0661	0.0661	0.0661
Total cost of production per kg live weight pig	**1.06**	**1.10**	**1.08**	**1.06**	**1.06**	**1.08**	**1.08**

Table A3.3: Breakdown of costs associated with the production of 1 kilogram of live weight slaughter pig at 110kg with each selected combination of abatement measures implemented. AD = Anaerobic Digestion, FSR = Frequent Slurry Removal, IMIN = Improved Insulation, ISD = Increased Slurry Dilution, IVE = Increased Ventilation Efficiency.

Costs (€)	**IVE & ISD**	**IVE & FSR**	**IVE & IMIN**	**AD & IVE**	**AD & IMIN**	**AD & FSR**	**IMIN & FSR & AD**	**IMIN & IVE & AD**	**IMIN & IVE & FSR & AD**	**IVE & FSR & AD**
Animal stock related costs	0.0849	0.0849	0.0849	0.0849	0.0849	0.0849	0.0849	0.0849	0.0849	0.0849
Feed & Water	0.695	0.695	0.695	0.695	0.695	0.695	0.695	0.695	0.695	0.695
Pig housing capital costs	0.0189	0.0189	0.0192	0.0189	0.0192	0.0189	0.0192	0.0192	0.0192	0.0189

Pig housing operating costs – incl. labour	0.163	0.176	0.160	0.161	0.166	0.182	0.182	0.160	0.176	0.176
Manure management capital costs	0.000274	0.000274	0.000274	0.000892	0.000892	0.00092	0.000892	0.000892	0.000892	0.000892
Manure management operating costs – incl. labour	0.0413	0.0309	0.0309	0.0644	0.0644	0.0644	0.0644	0.0644	0.0644	0.0644
Miscellaneous	0.0725	0.0725	0.0725	0.0687	0.0661	0.0661	0.0661	0.0725	0.0725	0.0725
Total cost of production per kg live weight pig	**1.08**	**1.08**	**1.06**	**1.09**	**1.10**	**1.11**	**1.11**	**1.10**	**1.11**	**1.11**

Table A3.4: Whole-farm Net Present Value over the time horizon, whole-farm Internal Rate of Return and whole-farm Annual Equivalent Value for all abatement measures tested. Stand-alone implementation presented above the double, horizontal line and combinations of abatement measures presented below. BAU = business as usual – baseline, IMIN = improved insulation, IVE = increased ventilation efficiency, FSR = frequent slurry removal, ISD = increased slurry dilution, AD = anaerobic digestion, Acid = slurry acidification

Abatement measure	**Whole-farm net present value (€)**	**Whole-farm annual equivalent value (€)**	**Whole-farm internal rate of return (%)**
Business As Usual – **BAU**	731,505	38,909	6.41
Anaerobic Digestion – **AD**	825,804	44,048	5.88
Increased Ventilation Efficiency – **IVE**	727,427	38,693	6.40
Improved Insulation – **IMIN**	693,103	36,867	6.16
Slurry separation – **SP**	616,565	32,888	5.81
Frequent Slurry Removal – **FSR**	341,746	18,178	4.56
Increased Slurry Dilution – **ISD**	286,799	15,298	4.29
Slurry Acidification – **Acid**	216,488	11,515	3.93
AD & IVE	920,492	49,099	6.21
AD & IMIN	804,328	42,903	5.76
IMIN & IVE & AD	781,303	41,675	5.68
IVE & IMIN	687,361	36,664	6.13
AD & FSR	436,045	23,259	4.49
IVE & FSR & AD	433,929	23,146	4.48
IVE & ISD	409,441	21,840	4.89
IMIN & FSR & AD	399,248	21,296	4.33
IMIN & IVE & FSR & AD	393,506	20,990	4.31
IVE & FSR	336,015	17,923	4.53
FSR & IMIN	303,203	16,173	4.33
IMIN & IVE & FSR	297,462	15,867	4.31
IMIN & IVE & ISD	242,298	12,924	4.04
IVE & FSR & Acid	-180,181	9,611	1.88

IMIN & IVE & Acid	171,987	9,174	3.69
Acid & IVE	498	26.6	2.83
Acid & IMIN	-34,183	-1,823	2.67
IMIN & IVE & FSR & ISD	-93,440	-4,984	2.35
IVE & FSR & ISD	-107,090	-5,712	2.26
FSR & ISD	-104,511	-5,575	2.28
IMIN & FSR & ISD	-141,771	-7,562	2.09
IMIN & ISD	-199,704	-10,652	1.79
IMIN & FSR & Acid	-214,863	-11,461	1.72
IMIN & IVE & FSR & Acid	-220,605	-11,767	1.68
Acid & FSR	-388,092	-20,701	0.939

Table A3.5: Cost of abatement of stand-alone measures for mitigation of each impact category assessed, expressed in euros per pollutant abated. If a measure did not exhibit abatement potential for an impact category, we reported the value as “not available”. IMIN = improved insulation, IVE = increased ventilation efficiency, FSR = frequent slurry removal, ISD = increased slurry dilution, AD = anaerobic digestion, Acid = slurry acidification, NA = not available.

Abatement cost per Impact category	IMIN	IVE	FSR	ISD	AD	Acid
NRRU (€ per g. Sb eq.)[37]	NA	0.147	NA	NA	-0.0493	NA
NREU (€ per GJ)[38]	0.00239	0.000229	NA	NA	0.000100	NA
GWP (€ per t. CO_2 eq.)[39]	0.47	0.0279	148,077	NA	-0.206	NA
AP (€ per t. SO_2^- eq.)[40]	7,031	1,970	126,712	5,670	NA	303
EP (€ per t. PO_4^{3-} eq.)[41]	384,774	20,760	2,891,883	186,032	NA	1,190

[37] Sb = antimony
[38] GJ = giga-joules
[39] CO_2 = carbon dioxide
[40] SO_2^- = sulphate
[41] PO_4^{3-} = phosphate

Table A3.6: Cost of abatement of the selected combinations of measures for mitigation of each impact category assessed, expressed in euros per pollutant abated. If a combination did not exhibit abatement potential for an impact category, we reported the value as "not available". IMIN = improved insulation, IVE = increased ventilation efficiency, FSR = frequent slurry removal, ISD = increased

Abatement cost per Impact category	**IVE & ISD**	**IVE & FSR**	**IVE & IMIN**	**AD & IVE**	**AD & IMIN**	**AD & FSR**	**IMIN & FSR & AD**	**IMIN & IVE & AD**	**IMIN & IVE & FSR & AD**	**IVE & FSR & AD**
NRRU (€ per g. Sb eq.)[42]	NA	67.6	1.07	-0.146	-0.0639	0.358	0.197	-0.0326	0.178	0.212
NREU (€ per GJ)[43]	1.44	0.102	0.00121	-0.000175	-0.0000590	0.000311	0.000267	-0.0000355	0.000244	0.000276
GWP (€ per t. CO_2 eq.)[44]	24.3	6.70	0.181	-0.237	-0.0843	0.705	0.381	-0.0350	0.270	0.397
AP (€ per t. SO_2^- eq.)[45]	4,174	106,689	5,901	NA	NA	NA	NA	NA	NA	NA
EP (€ per t. PO_4^{3-} eq.)[46]	211,834	3,118,992	311,000	NA	NA	NA	NA	NA	NA	NA

[42] Sb = antimony
[43] GJ = giga-joules
[44] CO_2 = carbon dioxide
[45] SO_2^- = sulphate
[46] PO_4^{3-} = phosphate

Table A4.1: Average environmental impact per unit of feed ingredients involved in diet formulations for growing and finishing pigs.

Feed ingredient	**Unit**	**NRRU (kg Sb eq.)**	**NREU (MJ)**	**GWP (kg CO_2 eq.)**	**AP (kg SO_2 eq.)**	**EP (kg PO_4^{3-} eq.)**	**LU (m^2)**	**AWARE (m^3)**	**BWSI (m^3)**
Barley grain	per kg	8.64 E-08	2.33	0.329	0.00453	0.00444	0.965	0.0261	0.000878
Wheat grain	per kg	7.83 E-08	2.22	0.352	0.00450	0.00489	0.835	0.0166	0.000418
Maize	per kg	1.78 E-07	3.95	0.500	0.00551	0.00541	1.06	0.349	0.0194
Wheat bran	per kg	7.07 E-08	5.74	0.595	0.00367	0.00309	0.505	0.0462	0.00148
Sunflower seed partly dehulled	per kg	3.50 E-07	11.1	1.23	0.00938	0.00688	6.59	2.44	0.0595
Rapeseed meal	per kg	1.64 E-07	5.57	1.26	0.00941	0.00882	2.75	0.0310	0.00110
Soybean meal	per kg	2.23 E-07	8.26	5.74	0.00506	0.00463	3.63	0.195	0.00319
Palm oil	per kg	1.83 E-07	8.44	8.77	0.00911	0.0132	2.29	0.0396	0.00135
Sugar beet molasses	per kg	2.68 E-08	1.87	0.168	0.00187	0.00167	0.184	0.00523	0.000247
Limestone, crushed	per kg	1.15 E-08	0.0770	0.00565	5.12 E-05	1.27 E-05	0.000240	0.00380	0.000125
Sodium chloride	per kg	9.90 E-08	1.81	0.168	0.00112	5.50 E-05	0.00	0.114	0.00369
L-Lysine HCl	per kg	9.14 E-07	246.	15.9	0.0209	0.00336	0.0588	339.	11.0
L-Threonine	per kg	9.14 E-07	246.	15.9	0.0209	0.00336	0.0588	339.	11.0
DL-Methionine	per kg	3.02 E-06	121.	5.93	0.0129	0.00192	0.00793	70.1	2.27
Tryptophane	per kg	4.77 E-05	210.	21.4	0.141	0.637	5.91	602.	19.5
Monocalcium phosphate	per kg	5.70 E-05	21.1	1.32	0.0182	0.00850	0.318	5.12	0.147
Water	per litre	7.92 E-11	9.55 E-05	1.61 E-05	5.50 E-08	2.27 E-08	4.37 E-06	0.0431	0.00140

Table A4.2: Average environmental impact per unit of construction material, technological equipment and energy involved in the pig housing and manure management components of pig fattening units.

Parameter	Unit	NRRU (kg Sb eq.)	NREU (MJ)	GWP (kg CO_2 eq.)	AP (kg SO_2 eq.)	EP (kg PO_4^{3-} eq.)	LU (m^2)	AWARE (m^3)	BWSI (m^3)
Electricity from grid	per MJ	2.24 E-09	0.174	0.0311	5.56 E-05	5.79 E-06	0.00	0.0117	0.000379
Electricity from natural gas	per MJ	6.34 E-07	2.51	0.168	0.00129	0.000169	0.0354	0.0415	0.00142
Concrete, 25MPa	per m^3	0.000324	1,564	248.	0.633	0.197	4.08	87.7	2.87
Polyvinylchloride, bulk polymerised (PVC)	per kg	4.31 E-07	46.3	2.16	0.00621	0.00107	0.00827	7.71	0.210
Heat distribution equipment, hydronic radiant floor heating, 150m^2	per unit	0.0224	31,489	3,402	13.9	3.23	43.3	876.	26.6
Blower and heat exchange unit, central, 600-1200 m^3/h	per unit	0.129	11,205	1,229	11.9	3.86	27.1	271.	8.32
Diesel fuel	per MJ	3.23 E-07	53.3	0.535	0.00553	0.000690	0.00677	0.130	0.00328
Operation, liquid manure storage and processing facility	per m^3	4.81 E-08	0.0479	0.00597	2.16 E-05	7.41 E-06	0.000591	0.00284	8.82 E-05
Liquid manure spreading, by vacuum tanker	per m^3	1.93 E-05	15.7	1.33	0.00846	0.00244	0.0659	0.117	0.00350
Transport, tractor and trailer, agricultural	kgkm	2.03 E-09	0.00464	0.000408	2.38 E-06	6.59 E-07	2.66 E-05	5.71 E-05	0.00174
Nitrogen fertiliser	per kg	1.10 E-05	40.1	2.81	0.0143	0.00355	0.0221	4.32	0.128
Phosphorus fertiliser	per kg	3.62 E-05	29.4	1.81	0.0150	0.00639	0.246	1.87	0.0580
Potassium fertiliser	per kg	2.20 E-05	13.5	1.02	0.00816	0.00213	0.0661	0.717	0.0205

Table A4.3: Characterisation factors for the environmental impact categories assessed, per unit of chemical substance emitted at pig housing and manure management.

Substance emitted	Unit	NRRU (kg Sb eq.)	NREU (MJ)	GWP (kg CO_2 eq.)	AP (kg SO_2 eq.)	EP (kg PO_4^{3-} eq.)	LU (m^2)	AWARE (m^3)	BWSI (m^3)
Ammonia	per kg	-	-	-	1.6	0.35	-	-	-
Carbon dioxide	per kg	-	-	1	-	-	-	-	-
Dinitrogen monoxide	per kg	-	-	265	-	0.27	-	-	-
Methane, biogenic	per kg	-	-	28	-	-	-	-	-
Nitrate	per kg	-	-	-	-	0.1	-	-	-
Nitrogen	per kg	-	-	-	-	0.42	-	-	-
Nitrogen oxides	per kg	-	-	-	0.5	0.13	-	-	-
Phosphorus	per kg	5.52 E-06	-	-	-	3.06	-	-	-

Table A5.1.: Available arable land near the pig farm for the four different geographic case studies, as obtained from the radial analysis in QGIS. N-LD = Case study less than 400m from Natura 2000 and in region of 2-3 pig farms per hectare. N-HD = Case study less than 400m from Natura 2000 and in region of 7-9 pig farms per hectare. LD = Case study further than 2km from Natura 2000 and in region of 2-3 pig farms per hectare. HD = Case study further than 2km from Natura 2000 and in region of 7-9 pig farms per hectare.

Distance from farm	**N-LD**	**HD**	**LD**	**N-HD**
	Available arable land (ha)	Available arable land (ha)	Available arable land (ha)	Available arable land (ha)
1 km	0	65.5	25.7	0
2 km	0	72.3	43.6	0
3 km	0	88.1	66.7	0
4 km	0	115	98.2	0
5 km	0	558	1,139	0
6 km	0	703	1,572	14.5
7 km	0	791	2,086	96.1
8 km	102	910	2,709	104
9 km	267	1,058	3,357	161
10 km	547	1,137	4,003	228
11 km	808	1,180	4,831	228
12 km	1,112	1,183	5,684	248
13 km	1,668	1,194	6,489	281
14 km	2,223	1,229	7,662	316
15 km	3,014	1,240	8,874	482
16 km	3,885	1,260	10,080	641
17 km	4,691	1,314	11,679	858

Table A5.2.: Annual, whole-farm environmental impact with the implementation of baseline and alternative manure management strategies for each impact category assessed and across the four geographic case studies. N-LD = Case study less than 400m from Natura 2000 in region of 2-3 pig farms per hectare. N-LD = Case study less than 400m from Natura 2000 and in region of 2-3 pig farms per hectare. N-HD = Case study less than 400m from Natura 2000 and in region of 7-9 pig farms per hectare. LD = Case study further than 2km from Natura 2000 and in region of 2-3 pig farms per hectare. HD = Case study further than 2km from Natura 2000 and in region of 7-9 pig farms per hectare

Environmental impact category	**Manure management strategy**	**N-LD**	**HD**	**LD**	**N-HD**
Global Warming Potential (t CO_2 eq.)	Baseline	5,330 (±3.26)	5,330 (±3.26)	5,330 (±3.26)	5,348 (±3.48)
	Anaerobic digestion	5,249 (±3.61)	5,249 (±3.61)	5,249 (±3.61)	5,281 (±3.70)
	Slurry Acidification	5,828 (±3.78)	5,828 (±3.78)	5,828 (±3.78)	5,855 (±4.04)
	Screw Press separation	5,756 (±4.28)	5,756 (±4.28)	5,756 (±4.28)	5,767 (±3.86)
Non-Renewable Resource Use (kg Sb eq.)	Baseline	1.71 (±0.0148)	1.71 (±0.0148)	1.71 (±0.0148)	1.77 (±0.0149)
	Anaerobic digestion	1.43 (±0.0192)	1.43 (±0.0192)	1.43 (±0.0192)	1.58 (±0.0195)
	Slurry Acidification	1.84 (±0.0168)	1.84 (±0.0168)	1.84 (±0.0168)	1.97 (±0.0163)
	Screw Press separation	1.60 (±0.0140)	1.60 (±0.0140)	1.60 (±0.0140)	1.68 (±0.0157)
Non-Renewable Energy Use (MJ)	Baseline	24,899 (±41.2)	24,899 (±41.2)	24,899 (±41.2)	25,070 (±42.8)
	Anaerobic digestion	17,399 (±42.3)	17,399 (±42.3)	17,399 (±42.3)	17,750 (±40.4)
	Slurry Acidification	25,243 (±42.8)	25,243 (±42.8)	25,243 (±42.8)	25,460 (±41.9)
	Screw Press separation	24,312 (±42.5)	24,312 (±42.5)	24,312 (±42.5)	24,461 (±40.5)
Available Water Resources – AWARE (m^3)	Baseline	6,970,156 (±12,328)	6,970,141 (±12,328)	6,970,152 (±12,328)	6,994,585 (±10,719)
	Anaerobic digestion	6,852,422 (±20,397)	6,852,408 (±20,397)	6,852,418 (±20,397)	6,875,765 (±16,030)
	Slurry Acidification	7,006,278 (±24,853)	7,006,265 (±24,853)	7,006,274 (±24,853)	7,016,122 (±30,278)
	Screw Press separation	6,990,877 (±11,595)	6,990,863 (±11,595)	6,990,873 (±11,595)	6,990,824 (±9,778)
Freshwater Eutrophication (kg PO_4^{3-} eq.)	Baseline	23.8 (±0.0358)	21.5 (±0.0324)	58.0 (±0.0652)	3.35 (±0.00489)
	Anaerobic digestion	24.1 (±0.0560)	21.7 (±0.0506)	59.3 (±0.487)	3.38 (±0.00641)
	Slurry Acidification	24.0 (±0.0391)	21.7 (±0.0353)	58.5 (±0.0676)	3.37 (±0.00455)
	Screw Press separation	23.3 (±0.0377)	21.1 (±0.0341)	55.8 (±0.0656)	3.23 (±0.00468)
Marine Eutrophication (t PO_4^{3-} eq.)	Baseline	9.99 (±0.00404)	10.0 (±0.00405)	9.99 (±0.00404)	9.98 (±0.00391)
	Anaerobic digestion	9.99 (±0.00390)	10.0 (±0.00391)	9.99 (±0.00390)	9.99 (±0.00394)
	Slurry Acidification	9.97 (±0.00381)	9.99 (±0.00382)	9.97 (±0.00381)	9.99 (±0.00393)

	Screw Press separation	9.75 (±0.00522)	9.77 (±0.00524)	9.75 (±0.00522)	9.75 (±0.00486)
Aquatic Acidification (t SO_2^- eq.)	Baseline	39.3 (±0.0917)	39.3 (±0.0917)	39.3 (±0.0917)	39.2 (±0.0904)
	Anaerobic digestion	47.7 (±0.111)	47.7 (±0.111)	47.7 (±0.111)	47.4 (±0.106)
	Slurry Acidification	21.3 (±0.0443)	21.3 (±0.0443)	21.3 (±0.0443)	21.3 (±0.0451)
	Screw Press separation	16.2 (±0.0271)	16.2 (±0.0271)	16.2 (±0.0271)	16.2 (±0.0276)
Terrestrial Acidification (t SO_2^- eq.)	Baseline	8.26 (±0.00814)	7.93 (±0.00803)	8.26 (±0.00814)	8.26 (±0.00868)
	Anaerobic digestion	3.13 (±0.00995)	2.73 (±0.00985)	3.13 (±0.00995)	3.14 (±0.00969)
	Slurry Acidification	8.10 (±0.00788)	7.87 (±0.00783)	8.10 (±0.00788)	8.10 (±0.00788)
	Screw Press separation	8.26 (±0.00903)	7.69 (±0.00875)	8.26 (±0.00903)	8.25 (±0.00810)