Arla Foods FarmTool v2021

- Updates and adding new technologies




2.-0 LCA consultants

Preface

This report documents new modules in the Arla FarmTool v2021, which is a detailed life cycle model for milk production at farm level. The new modules are added to the Arla FarmTool v2016 model, which is documented in:

- **Dalgaard R, Schmidt J, Cenian K (2016)**. Life cycle assessment of milk - National baselines for Germany, Denmark, Sweden and United Kingdom 1990 and 2012. Arla Foods, Aarhus, Denmark http://lca-net.com/p/2324
- **Dalgaard R, Schmidt J, Flysjö A (2014)**. Generic model for calculating carbon footprint of milk using four different LCA modelling approaches. Journal of Cleaner Production 73:146-153 https://lca-net.com/p/580
- **Schmidt J, Dalgaard R (2012)**. National and farm level carbon footprint of milk – Methodology and results for Danish and Swedish milk 2005 at farm gate. Arla Foods, Aarhus, Denmark. http://lca-net.com/p/220
- **Dalgaard R, Schmidt J (2012)**. National and farm level carbon footprint of milk – Life cycle inventory for Danish and Swedish milk 2005 at farm gate. Arla Foods, Aarhus, Denmark. http://lca-net.com/p/222

2.-0 LCA consultants, Aalborg, Denmark

LCA

When citing the current report, please use the following reference:

When citing this report, please use the following reference:
Schmidt J and Dalgaard R (2021). Arla Foods FarmTool v2021 - Updates and adding new technologies. Arla Foods, Aarhus, Denmark

December 2021

CONTENTS

Abbreviations **5**

1 Introduction **6**

1.1 LCA of milk at Arla Foods 6

2 Goal and scope of the study **8**

2.1 Functional unit 8

2.2 Product system 8

2.3 Foreground system: Data collection 9

2.4 Background system: Data for purchased crops/feed and LCA databases 10

2.5 Delimitation of time and geography 10

2.6 LCA approach compliance with two different guidelines/standards 12

2.7 Land use changes 15

2.8 Life cycle impact assessment 15

3 FarmTool module: Animals **16**

3.1 Input data on animals 16

3.2 Milk output 17

3.3 Beef output 17

3.4 Feed intake 18

3.5 Methane from enteric fermentation 20

4 FarmTool module: housing and manure storage, treatment and land application **22**

4.1 Housing 22

4.2 Manure storage 23

4.3 Anaerobic digestion of slurry 24

4.4 Land application of manure 26

4.5 Summary of the LCI of environmental technologies 32

5 FarmTool module: crop cultivation **36**

5.1 Organic soils 36

6 FarmTool module: Feed **37**

6.1 Purchased concentrates and option for specifications 37

6.2 Additional types of purchased feed modelled based on existing feed in the model 40

7 FarmTool module: Energy **41**

7.1 Biodiesel (HVO and RME) 41

7.2 Electricity 42

8 Uncertainties **45**

9 Sensitivity, completeness and consistency checks **47**

9.1 Sensitivity check 47

9.2 Completeness check 47

9.3 Consistency check 47

10 Conclusion **49**

11 References **50**

Appendix 1: Modelling of heat 54
Heat use in the agricultural sector 54
District heating 54
Biomass production and combustion 55
Appendix 2: Feed properties 57

Abbreviations

CH_4	Methane
CHP	Combined heat and power
FA	Fatty acid
FarmTool v2016	The Arla FarmTool obtained as the version described in Dalgaard et al. (2016)
FarmTool v2021	The Arla FarmTool obtained as the version described in the current report.
GE	Gross energy
HVO	Biodiesel: Hydrotreated vegetable oil
N_2O	Nitrous oxide
NH_3	Ammonia
RME	Biodiesel: Rapeseed methyl ester
SBM	Soybean meal
UNFCCC	United Nations Framework Convention on Climate Change

1 Introduction

In their work with sustainability, Arla Foods focusses on tracking the environmental impact of their main raw material, raw milk, – both at farm level, and at the national level. Arla is using this information as baselines and benchmarks for their environmental goals, as a tool for individual milk farmers, and for gaining knowledge about the environmental impacts and on how to mitigating impacts. The current report presents a comprehensive update (v2021 version) of the previous version of the FarmTool (v2016), which has been used to track and benchmark GHG emissions per kg milk at farm level.

The purpose of updating the FarmTool is to include a comprehensive range of best techniques for mitigating GHG emissions in the milk life cycle production system. The new modules of best techniques include various alternative techniques for:

- Manure acidification
- Anaerobic digestion of manure
- Renewable energy

Besides adding new modules enabling for modelling the effect of best techniques, the update also includes a significant increase in the granularity of data input types to be included in the calculations. This includes:

- New crop types
- Option to specify the time for incorporation of solid manure/deep litter after land application
- Option to specify feed properties of concentrates:
    - content of proteins
    - content of fatty acids (this option is currently not open to users of the tool)
    - indicate if the concentrate is soy-free

Further, the update includes a number of changes of the methodology. The most significant change is the way the beef by-product (live animals) is estimated. Before, this was based on specification of the number of animals sent to slaughterhouse and their weights. Due to lack of data on this at the farm level as well as uncertainties caused by temporal variations, it has been decided to change the approach so that the by-product of live animals to slaughterhouse is now calculated based on generic data on weight gain.

1.1 LCA of milk at Arla Foods

National baselines

Life cycle assessment of milk at Arla foods started in 2011 with a study on Danish and Swedish milk produced in 2005. The developed model was intended for being used for obtaining national baselines as well as for being used to calculate carbon footprints of milk production on individual farms. The outcome of this study is published in:

- **Schmidt J, Dalgaard R (2012)**. National and farm level carbon footprint of milk – Methodology and results for Danish and Swedish milk 2005 at farm gate. Arla Foods, Aarhus, Denmark. http://lca-net.com/p/220
- **Dalgaard R, Schmidt J (2012a)**. National and farm level carbon footprint of milk – Life cycle inventory for Danish and Swedish milk 2005 at farm gate. Arla Foods, Aarhus, Denmark. http://lca-net.com/p/222
- **Dalgaard R, Schmidt J, Flysjö A (2014)**. Generic model for calculating carbon footprint of milk using four different LCA modelling approaches. Journal of Cleaner Production 73:146‐153

In 2012-2013, national baselines for Denmark and Sweden for 1990 were conducted (Dalgaard and Schmidt 2012b). The purpose of these older inventories was to have data for the reference year, to which Arla defines and benchmarks their environmental performance targets. In 2013, national baselines for 1990 for Germany and United Kingdom were also established. These baselines are published in:

- **Dalgaard R and Schmidt J (2012b)**. National carbon footprint of milk - Life cycle assessment of Danish and Swedish milk 1990 at farm gate. Arla Foods, Aarhus, Denmark
- **De Rosa M, Dalgaard R, Schmidt J (2013)**. National carbon footprint of milk - Life cycle assessment of British and German milk 1990 at farm gate. Arla Foods, Aarhus http://lca-net.com/p/2329

In 2015-2016, baselines for 2012 for Denmark, Germany, Sweden and United Kingdom were established. The 2012 baselines were benchmarked with the 1990 baselines for the four countries. The outcome of this is published in:

- **Dalgaard R, Schmidt J, Cenian K (2016)**. Life cycle assessment of milk - National baselines for Germany, Denmark, Sweden and United Kingdom 1990 and 2012. Arla Foods, Aarhus, Denmark http://lca-net.com/p/2324

FarmTool

Concurrently with the establishment of national baselines, a tool to calculate carbon footprints of milk produced at farm level in Germany, Denmark, Sweden and United Kingdom has been developed: The **Arla FarmTool**. The tool is based on the model used for the national baselines, where the basic difference is, that instead of populating the model with national figures on the milk and crop systems, it is populated with farm specific input data. The background data of the FarmTool, e.g. imported feed, electricity etc., links directly to the national baseline models.

The first version of the tool was developed in 2011-2012 (FarmTool v2012). The FarmTool is regularly maintained and adjusted. In 2016, with the development of the 2012 baselines, a major update of the FarmTool was made: FarmTool v2016.

The current report documents a major update of the FarmTool v2016. This will be referred to as the FarmTool v2021 in the following.

2 Goal and scope of the study

The goal of the FarmTool is to enable for calculating detailed GHG emissions for all farms supplying milk to Arla Foods. This is described here: https://www.arla.com/sustainability/sustainable-dairy-farming/how-we-measure-dairy-farmings-carbon-footprint/

The LCA is carried out in accordance with the ISO standards on LCA: ISO 14040 (2006) and ISO 14044 (2006). According to the ISO standards an LCA consists of four phases:

1. Definition of goal and scope
2. Life cycle inventory (LCI)
3. Life cycle impact assessment (LCIA)
4. Life cycle interpretation

Note that part of this chapter is a reproduction of chapter 2 of Dalgaard et al. (2016).

This section documents the first phase of the LCA used for the Arla FarmTool for milk at farm gate in DE, DK, SE and UK. The first phase includes description of the purpose of the study, definition of the functional unit, an overview of the applied methods and an overview of the relevant processes (system boundary).

2.1 Functional unit

The functional unit is 1 kg fat and protein corrected milk (FPCM). Bulletin of the International Dairy Federation 479/2015. International Dairy Federation. FPCM is calculated by multiplying milk production by the ratio of the energy content of a specific farm's (or country/region) milk, to the energy content of standard milk with 4% fat and 3.3% crude protein:

Equation 2.1

$$\text{FPCM} = \text{milk} \cdot (0.1226 \cdot \text{Fat\%} + 0.0776 \cdot \text{CP\%} + 0.2534)$$

Where:

FPCM = fat and protein corrected milk defined as raw milk with 4.10% fat and 3.30% protein
Milk = raw milk production (kg)
Fat% = content of fat (%)
CP = content of crude protein (%)

2.2 Product system

Milk is produced in the cattle system. Generally, the cattle system can be divided into a milk system and a beef system. The milk system is optimised in order to produce milk, and it produces meat from surplus calves as a by-product of the system. The beef system is characterised by having meat as the main product and no milk production.

In the milk system, the milking cows produce the milk. Approximately one time a year, the cow must have a calf for maintaining high milk production. Some of the heifer calves are raised to replace milking cows to maintain the herd, while surplus heifers are slaughtered. Generally, all bull calves are raised for slaughter. A heifer becomes a milking cow when it gives birth to its first calf.

Cattle have their feed from the plant cultivation system, i.e. plant material cultivated on arable or grassland, or from the food industry, where it is mainly by-products, e.g. molasses from sugar manufacturing or rapeseed meal from rapeseed oil manufacturing. In some cases, feed is the main product in the food industry, e.g. soymeal from the soybean oil mill.

The plant cultivation system involves permanent grassland as well as annual and perennial crops. Some cultivation requires significant inputs of mechanical energy (traction) and chemicals (fertilisers and pesticides), whereas others are more extensive. The food industry involves the processing of crops from the plant cultivation system.

The milk system, plant cultivation system and food industries are illustrated in **Figure 2.1**.

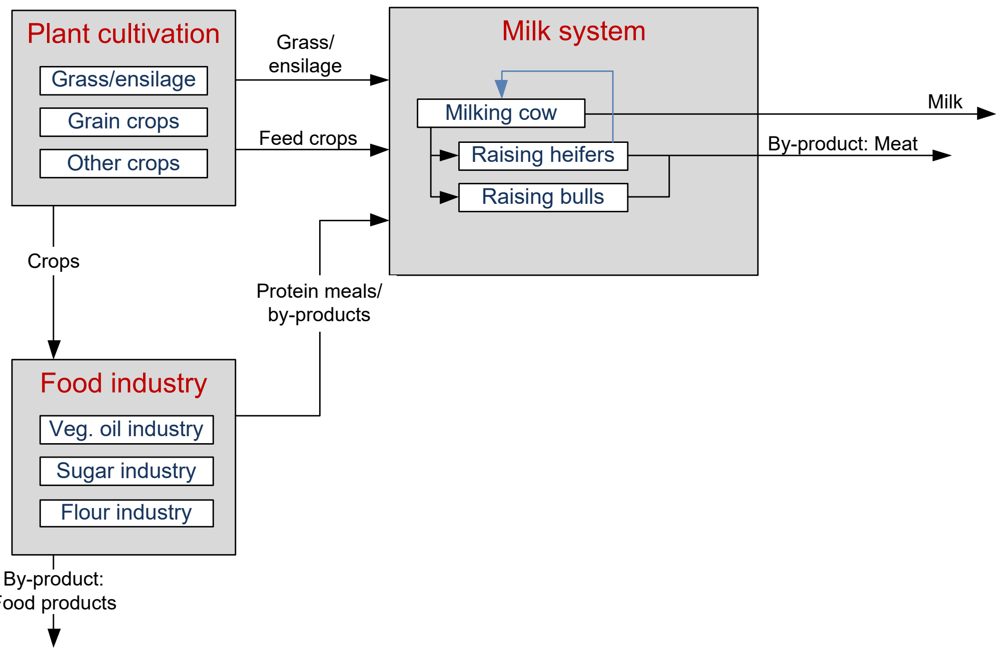

Figure 2.1: Overview of the milk production system. In addition to the shown product stages, there are also several other involved activities, such as transportation, electricity generation, fuel production, fertiliser production etc.

When calculating the carbon footprint for milk, the major GHG-emissions from the milk system are related to methane (CH_4) from enteric fermentation and manure management, as well as nitrous oxide (N_2O) emissions from manure management. The most important upstream contribution is related to the production of feed. Here nitrous oxide emissions from the field (from fertiliser application) and from the production of fertilisers are the major GHG-emissions. Other GHG-emissions in the system such as diesel for traction, electricity for the milking machinery etc. are generally less important. (Dalgaard et al. 2014).

2.3 Foreground system: Data collection

The data used for the calculations for GHG emissions at farm level are primarily based on primary data provided by each farm. Data for the individual farms are gathered annually via "Arlagården". More information is available here: https://www.arla.com/sustainability/sustainable-dairy-farming/how-we-measure-dairy-farmings-carbon-footprint/#how-is-a-climate-check-conducted

The specific activities inventoried at the farm level are indicated in **Table 2.1** below.

2.4 Background system: Data for purchased crops/feed and LCA databases

All emissions taking place outside the dairy farms are accounted for in the background system, e.g. emissions from the production of purchased feed, energy etc. The background system includes specifically inventoried animal activities, crops and feed as well as data obtained directly from LCA databases.

The specifically inventoried animal systems, crops and feed are described in Dalgaard et al. (2016) and Dalgaard and Schmidt (2012). All these data refers to 2012.

The part of the product system that is not included as part of the farms or the specifically inventoried animals, crops and feed is covered by LCA databases. This includes production of fertiliser, electricity, fuels, chemicals, machinery, and buildings. These data are mainly based on ecoinvent v2, while fertilisers are updated based on based on European Commission (2007, Table III) and electricity is based on ecoinvent v3. This is described in detail in chapter 3 of Dalgaard et al. (2016). It should be noted that the data used for the background are becoming outdated. The background system will be updated in 2022. Further, it should be noted that the background system based on ecoinvent v2 and 3 account for a relatively small part of the overall GHG emissions; <10%.

2.5 Delimitation of time and geography

The current report presents a model used for farms mainly in DE, DK, SE and UK in 2020 an onwards.

The life cycle inventory includes the following of inventoried activities:

- Cattle system,
- Plant cultivation system,
- Food industry system, and
- General activities which are used in several other activities, such as electricity, transport, fuels etc.

The table below summarises which activities and countries that are included in the inventory of the cattle system, plant cultivation system, and food industry. The column "Farm" indicates when the activity is parameterised to be modelled at the farm level. This means that the activity is established as a parameterised dataset without data. The actual data are entered by the user of the FarmTool.

Table 2.1: List of inventoried cattle, plant cultivation and food industry activities in the current study. When the activities supply more than one product, the product outputs are indicated in square brackets [].

Inventoried activities	Farm	BR	DE	DK	FR	MY/ID	SE	UA	UK	EU
Cattle system										
Milk system (cows, heifers and bulls)	X		X	X			X		X	
Beef system (cows, heifers and bulls)	X	X								
Plant cultivation system										
Extensive permanent pasture	X	X	X	X			X		X	
Intensive permanent pasture	X									
Temporary pasture	X									
Rotation grass	X		X	X			X		X	
Roughage, maize ensilage	X		X	X			X		X	
Grain whole crop	X									
Legume whole crop	X									
Barley	X		X	X			X	X	X	X
Wheat	X		X	X			X		X	X
Oat	X		X	X			X		X	
Corn										X
Soybean		X								
Rapeseed	X									X
Sunflower					X					
Sugar beet			X	X			X		X	
Oil palm fruit						X				
Broad bean	X		X	X			X		X	
Triticale	X		X	X			X		X	
Food industries										
Palm oil mill [oil and kernel]						X				
Palm oil refinery [oil and free fatty acids]						X				
Palm kernel oil mill [oil and meal]						X				
Palm kernel oil refinery [oil and free fatty acids]						X				
Soybean oil mill [oil and meal]		X								
Soybean oil refinery [oil and free fatty acids]		X								
Rapeseed oil mill [oil and meal]										X
Rapeseed oil refinery [oil and free fatty acids]										X
Sunflower oil mill [oil and meal]					X					
Sugar mill [sugar, molasses, beet pulp]			X	X			X		X	
Flour mill [flour and wheat bran]										X
Malthouse [malt and malt sprouts]			X	X			X		X	
Brewery [Beer and brewer's grain]			X	X			X		X	
Bioethanol production [bioethanol and DDGS]										X
HVO biodiesel production										X
RME biodiesel production										X
Milk powder production			X	X			X		X	
Milk replacer production			X	X			X		X	

2.6 LCA approach compliance with two different guidelines/standards

A key challenge for Arla Foods is that different methods for calculating the carbon footprint (CF) / LCA results are often used in the countries where Arla Foods operates. Arla Foods therefore needs a flexible tool that enables different types of modelling depending on the context. It should be possible to calculate the CF at farm level and national level according to the used practises in the given country, but it should also be possible to compare results between countries and to calculate the aggregated CF at corporate level.

Therefore, the life cycle assessment is modelled in a flexible framework, where it is possible to switch between different modelling assumptions and where different levels of completeness in data can be switched on and off. The included standards/guidelines are:

- **Consequential model:** Consistent interpretation of ISO 14040/44, where included suppliers are the most likely to be affected and allocation is avoided by substitution. The following standards/methodologies are followed: ISO 14044 (2006), Weidema et al. (2009). Further, the quality guideline for ecoinvent v3 (consequential version) is to a large extent followed (Weidema et al. 2013).
- **IDF Guideline:** Attributional model, which implies a normative interpretation of ISO 14040/44, where market average mixes of suppliers and allocation are carried out by use of allocation. The specific requirements from the IDF Guideline are used (IDF 2015).

The purpose of the IDF model is to carry out the life cycle GHG calculations following the guideline that is widely acknowledged within the dairy sector. The purpose of the consequential model is to establish a cause-effect based calculation of the effects of demanding the functional unit.

The features of the two standards/guidelines are summarised in the table below.

Table 2.2: Description of the key elements of the modelling in LCI in the applied modelling approaches/standards.

Elements in modelling	Description
ISO 14040/44: Consequential modelling (ISO 14040, 2006; ISO 14044, 2006; Weidema et al. 2011)	
Included suppliers	The included suppliers represent the actual production mix (ISO14044, section 4.3.3.1). This is interpreted as the actual affected suppliers by a change in demand. As default, the actual production mix is regarded as the average product mix where constrained suppliers are excluded (Weidema et al. 2009).
Multiple-output activities	Whenever possible, allocation should be avoided (ISO 14044, section 4.3.4.2). The reference product(s), i.e. the determining co-product(s) is determined, and the remaining co-products are regarded as by-products which can directly substitute other products or as material to treatment. All exchanges are ascribed to the reference product(s) including the avoided exchanges related to the displaced activities due to by-products.
Completeness	The applied cut-off criterion is close to 0%, i.e. all transactions in the product system are included – only with the below exceptions. Some transactions are inventoried in detail whereas other are obtained a more generic data from LCI databases (ecoinvent) and input-output databases. The following minor flows have not been included: production and use of pesticides, refrigerants as well as emissions from disposal of waste from packaging.
IDF guide to standard LCA methodology for the dairy industry: attributional (IDF 2015)	
Included suppliers	The included suppliers represent the average market mix including constrained suppliers (IDF 2015, section 1.4).
Multiple-output activities	Specific guidelines are provided for: Feed (economical allocation), milk/meat (specified formula), onsite CHP (substitution), manure (cut-off) (IDF 2015, section 6.3). It should be noted that the Arla FarmTool deviates from the IDF requirement on a cut-off modelling for manure. The applied model ascribes the entire effects related to manure to the animal production, while crop production fully relies on mineral fertiliser. As long as there is no significant transactions of manure crossing the farm boundary, this deviation does not affect the results. For beef production, the IDF Guideline draws an allocation boundary following the farm boundary, i.e. the allocation between milk and live animals is done at the farm gate, and not at the point of substitution, i.e. at the slaughterhouse where the animals are fully raised.
Completeness	The IDF Guidelines does not define a cut-off criterion. IDF does not specifically exclude any groups of inventory items. It has been chosen to include the same level of completeness as in ecoinvent. I.e. capital goods are included, while the use of services (modelled using input-output data) are cut-off. Further, the following minor flows have not been included: production and use of pesticides, refrigerants as well as emissions from disposal of waste from packaging.

Notes of the IDF model

In the FarmTool v2021, the IDF switch has been updated to reflect the most recent version of the Common Carbon Footprint Approach published from the International Dairy Federation (IDF 2015). Previously, the IDF switch of the FarmTool used IDF (2010).

The allocation between milk and meat has been updated from **Equation 2.2** (FarmTool v2016) to **Equation 2.3** (current v2021).

Equation 2.2: Allocation according to IDF (2010)

$$AF_{milk} = 1 - 5.7717 * M_{meat}/M_{milk}$$

Equation 2.3: Allocation according to IDF (2015)

$$AF_{milk} = 1 - 6.04 * M_{meat}/M_{milk}$$

Where,

AF_{milk} is the allocation factor for milk

M_{meat} is the sum of live weight of all animals sold including bull calves and culled mature animals

M_{milk} is the sum of milk sold corrected to 4% fat and 3.3% protein

The implementation of the IDF model in the FarmTool includes a few deviations compared to IDF (2015). The effect on the calculated results on GHG emissions per kg FPCM are negligible, and the changes are made in order to ensure consistency in the calculations and to correct for obvious errors. The deviations include:

1. Heat by-product from anaerobic digestion: The substituted sources of heat are the actual ones instead of natural gas and coal
2. Substitution is applied instead of allocation for heat produced on CHP outside the agricultural system
3. Modelling of manure is entirely allocated to animal activities

Ad. 1: According to IDF (2015, p 34), the energy surplus from a farm having anaerobic digestion shall be assumed to substitute heat from natural gas or coal. Firstly, this assumption is inconsistent compared to the way electricity is modelled, where actual national averages are used. Secondly, as described in **Table 0.1**, considerable amounts of energy used in agriculture is renewable energy. Hence, it seems inconsistent to assume that heat generation in agriculture should only substitute natural gas and coal. Therefore, we have changed the substituted energy to reflect the average mix of heat supply to agriculture in the respective countries.

Ad. 2: According to IDF (2015, p 34), co-product handling of combined heat and power (CHP) plants should/could follow the guidelines in the GHG Protocol. According to the GHG Protocol guideline referred to in IDF (2015), various forms of allocation between heat and electricity can be applied. Applying allocation between the produced heat and electricity is inconsistent with the modelling of energy surplus from farms (from burning biogas in CHPs), where this substitutes alternative heat and electricity production. Therefore, we have modelled the CHPs in other parts of the product system consistently with the CHPs in the milk system by using substitution. This is modelling assumption is applied when modelling the average heat supply, which includes district heating, where CHPs are part of the mix in most countries. For CHPs, heat is assumed to be the reference flow, while electricity is the by-product (Schmidt et al. 2011).

Ad. 3: According to IDF (2015, p 30), emissions related to manure are assigned to the animal system up to the point of field application, while emissions from manure in the field are assigned to crop cultivation. Since manure treatment such as anaerobic digestion and acidification affects both the emissions before and after field application and since both treated and untreated manure may be imported/exported from the farms, the IDF approach would imply imbalances in the sense that all produced manure may be modelled with different technologies than all used manure.

Besides being inconsistent, the IDF approach would also require additional data when manure is imported to the farm, i.e. if the manure has been acidified and or anaerobically digested.

Further, besides being inconsistent and more data requiring, the IDF approach would highly over complicate the modelling of manure treatment and land application because both the manure treatment activities and the crop cultivation activities would be affected. Instead, we have chosen to account for the entire effect of the technology mix related to manure treatment and land application, so that all differences in crop emissions are accounted in the manure treatment/land application activity. As long as the farm is using all its manure on its own crops, and as long as all the farm's own crops are used for their own animals, there is no effects on the result from this modelling choice. If the farm exports manure and if the farm exports crops, there will be minor differences in the results compared to the IDF approach.

2.7 Land use changes

The consequential version includes indirect land use changes according to Schmidt et al. (2015). This is described in section 3.9 in Dalgaard et al. (2016).

The IDF version does not include land use changes. The FarmTool has a feature that enables to switch on direct land use changes according to PAS 2050. However, this feature is turned off by default.

2.8 Life cycle impact assessment

The current study only presents results for global warming. When translating GHG emissions into carbon dioxide equivalents, the IPCC's global warming potential (GWP100) has been used. The emission factors from IPCC's fifths assessment report have been used (IPCC 2013). In Table 2.3, the most important GHG emissions are listed.

Table 2.3: Applied GWP100 factors in the Arla FarmTool. LUC = land use change.

Emission	GWP100 (kg CO_2-eq/kg)
Carbon dioxide, fossil	1
Carbon dioxide, biogenic	0
Carbon dioxide, biogenic: LUC emissions, IDF, not used in default calculation	1
Carbon dioxide, biogenic: accelerated LUC emissions, consequential, see Schmidt et al. (2015)	0.00772
Methane, biogenic	28
Methane, fossil	30
Nitrous oxide	265

3 FarmTool module: Animals

The starting point for the modelling of emissions on the farm as well as upstream emissions related to the production of feed, manure treatment etc. is data on the herd of animals at the farm. This includes basic data on the number of animals, age of animals, milk production, grassing and housing systems. These input data are used to calculate the output of beef and feed requirement. The input data on housing system are used to calculate emissions from housing and storage of manure. These calculations are further described in chapter 4.

3.1 Input data on animals

Below, in **Textbox 3.1** the input data on animals to the FarmTool are summarised.

Textbox 3.1. Input data to the FarmTool on animals

Number of animals

- Number of animals (annual averages) for:
  - cows,
  - heifers (replacement and beef heifers),
  - bulls (bull calves from newborn to weaning and bulls after weaning)
- Number of born claves (live and stillborn)
- Number of dead or euthanized animals
  - cows,
  - heifers (replacement and beef heifers),
  - bulls (bull calves from newborn to weaning and bulls after weaning)
- Number of heifers are sent off-farm for and returned from off-farm rearing

Age of animals

- heifers at first calving
- heifers sent off-farm for and returned from off-farm rearing
- dead or euthanized heifers
- dead or euthanized bull calves
- dead or euthanized fattening bulls/steers

Milk production

- Production of milk (delivered to dairy, not energy corrected)
- Fat content in raw milk
- Protein content in raw milk

Grassing: For each animal category,

- Number of animals that have access to grazing
- Days of the year the animals graze
- Hours per day the animals graze

Housing system: The housing system is indicated as number of each animal category in:

- Cubicle shed
  - with a slatted floor area
  - with a slatted floor area and scrapers
  - with a solid floor
  - with a solid floor
- Fully slatted floor yards
- Straw yards
  - with a slatted floor area
  - with a slatted floor area and scrapers
  - with a slatted floor area and scrapers
  - with a solid floor area
  - with slatted floor area
- Tethered
  - slurry based system
  - solid manure system

3.2 Milk output

The input data specifies raw milk delivered to dairy (not energy corrected). The tool operates with a standard loss of milk (difference between produced milk and delivered milk to dairy) at 5%. This number is based on empiric data from Arla. The raw milk is converted to fat and protein corrected milk (FPCM) using **Equation 2.1**.

3.3 Beef output

The beef output influences the results via substitution (consequential model) or via the calculated allocation factor (IDF model). For the consequential model, it is observed that all offspring of milk cows are related to the milk production, and hence all beef outputs after the fattening of both excess heifers and bulls is included as a by-product of milk production. Obviously, the beef from the dairy cow itself is also considered as a by-product. For the IDF model, only beef from dairy cows, replacement heifers and small bull calves (from newborn to weaning) are included. The rest is 100% allocated to beef.

The quantity of beef by-products, i.e. live weight animal for export, produced at the farm is estimated based on:

- Standard weight gain data, see **Table 3.1**.
- The time the animals are present at the farm.
- Number of dead and euthanized animals
- Weight of dead and euthanized animals. This is estimated from Table 3.2 and an assumed weight of dead born calves at 40 kg except for Jersey and Guernsey breeds, where a weight at 25 kg is assumed.

Only weight gain at the farm is included. This implies that the purchase of animals comes with zero GHG emissions.

The approach described above is different from the FarmTool v2016, where the beef output was based on reported data on number of inputs/outputs of animals and their weights by the milk farmers. However, based on user experiences, the data on the weight of animals were often not known. Further, changes in stock of animals from one to another accounting period introduced uncertainties. Therefore, it was decided to change approach so that the beef output is estimated based on weight gain data in FarmTool v2021.

Table 3.1. Weight gain in units of kg/year of animals (data retrieved from Arla).

Breed	Dairy cows	Heifers (0 days - first calving)	Bull calves (0 days – weaning)	Young bulls (weaning – slaughter/export)
Holstein, Black	40	256	381	426
Holstein, Red	40	256	381	426
Friesian	40	256	381	435
Danish Red	40	256	381	426
Swedish Red	40	256	381	426
Jersey	25	192	254	331
Guernsey	30	210	300	360
Ayrshire	35	235	340	400
Brown Swiss	40	256	381	435
Angler	40	256	381	435
Cross Breed, large > 600 kg	40	256	381	435
Cross Breed, small < 600 kg	35	235	340	400
Fleckvieh/Simmental	45	256	381	460
Montbeliarde	42	256	381	450
Normanne	45	256	381	460
Shorthorn	45	256	381	460
Other (large breeds)	40	256	381	435

3.4 Feed intake

The feed requirement can be established in two different ways in the Arla Farm tool:

1. Manual specification of feed
2. Calculation of feed requirement

The first bullet above is relevant when farms have feed monitoring, which includes monitoring of all purchased feed plus homegrown roughage.

In cases where the farmer does not have feed monitoring, the model calculates the feed requirement, see next section.

Calculation of feed requirement

The feed requirement is calculated using the NorFor model (Volden 2011) for cows and IPCC (2006) for heifers and bulls.

The implementation of the IPCC (2006) method, used for other animal categories than cows, is described in Schmidt and Dalgaard (2012, section 6.3). The net energy (NE) requirement for cows according to NorFor can be calculated as described in **Equation 3.1**.

Equation 3.1

$$\mathbf{NE} = NE_{maint} + NEL_{milk} + NE_{gest} + NEL_{gain}$$

where

$\mathbf{NE_{maint}}$ is daily energy requirement for maintenance, MJ NE/day (see **Equation 3.2**)

$\mathbf{NEL_{milk}}$ is daily energy requirement for production of ECM, MJ NEL/day (ECM is energy corrected milk) (see **Equation 3.3**)

$\mathbf{NE_{gest}}$ is the daily NE requirement for gestation in cows and heifers, MJ/day (see **Equation 3.4**)

$\mathbf{NEL_{gain}}$ the daily energy requirement for growth in primiparous cows, MJ/day (see **Equation 3.5**)

In the following, each of the terms in **Equation 3.1** are described.

Equation 3.2

$$\mathbf{NE_{maint}} = factor1 \cdot BW0.75 \cdot NE_{exercise}$$

where

$\mathbf{factor_1}$ = 0.2926 (Volden 2011, p 85)

BW is the weight of the animal, kg (see **Table 3.2**)

$\mathbf{NE_{exercise}}$ is 1 for tied-up animals and 1.1 for loose-housed or grazing animals (Volden 2011, p 85)

Table 3.2. Average weights in kilos of animals (data retrieved from Arla).

Breed	Dairy cows	Heifers (0 days - first calving)	Bull calves (0 days – weaning)	Young bulls (weaning – slaughter/export)
Holstein, Black	650	358	57	279
Holstein, Red	650	358	57	279
Friesian	650	358	57	279
Danish Red	600	330	54	276
Swedish Red	600	330	54	276
Jersey	450	243	38	210
Guernsey	450	243	38	210
Ayrshire	600	330	54	276
Brown Swiss	650	358	57	279
Angler	600	330	54	276
Cross Breed, large > 600 kg	650	358	57	279
Cross Breed, small < 600 kg	550	303	54	276
Fleckvieh/Simmental	750	413	63	296
Montbeliarde	650	358	60	295
Normanne	750	413	63	303
Shorthorn	600	330	54	276
Other (large breeds)	650	358	57	279

Equation 3.3

$$\mathbf{NEL_{milk}} = 3.14 \cdot ECM / 365$$

where

ECM is the annual milk yield ex cow measured as energy corrected milk.

ECM = raw milk · (0.383 · fat_cont · 100 + 0.242 · protein_cont · 100 + 0.7832) / 3.14

where raw milk is the annual milk yield per cow (ex cow), fat_cont and protein_cont are the fat and protein contents of the raw milk.

Equation 3.4

$$\mathbf{NE_{gest}} = BW / 600\ e^{0.0144*Gest\_day-1.1595}$$

where

BW is the average live body weight (BW) of the animals in the population, see **Table 3.2**.

Gest_day is days in gestation. This is set to 150 (Nielsen 2020).

Equation 3.5

$$\mathbf{NEL_{gain}} = 0.00145 \cdot BW + 12.48 * WG / 1000 + 0.68$$

where

BW is the average live body weight (BW) of the animals in the population, see **Table 3.2**.

WG is the daily weight gain (kg), see **Table 3.1**, which show the annual weight gain.

Feed properties

For different calculations in the model, the feed flows are converted into kg dry matter, kg protein, kg fatty acid, MJ digestible energy, MJ net energy for lactation, MJ gross energy. These conversions are based on feed properties, which are specified per type of feed input (see **Appendix 2: Feed properties**).

Feed losses

Standard factors for feed loss of incoming feed to the farm are used: 5% for grains and by-products and 10% for roughage. These factors are based on estimates from Arla.

When farmers provide data on purchased and produced feed, then the feed intake is calculated by multiplying with (100% minus loss%). When the feed requirement = feed intake is calculated, then the produced feed is calculated by dividing with (100% minus loss%).

No emissions are included in relation to decay of feed losses.

3.5 Methane from enteric fermentation

CH_4 from enteric fermentation is calculated using IPCC (2006). This is described in Schmidt and Dalgaard (2012). However, this calculation does not take into account that the amount of fatty acids in the feed has an effect on methane from enteric fermentation. The higher fatty acids content, the lower are the methane emissions. In the FarmTool v2021, the calculated CH_4 according to IPCC (2006) is adjusted to account for the effect of fatty acids in the feed.

In Mogensen et al. (2018, p 80) a formula for the relationship between methane production and fatty acid content in the feed ration is presented, see **Equation 3.6**.

Equation 3.6

$$\text{Methane (MJ/day)} = 1.39 \cdot \text{DM\_intake (kg/day)} - 0.091 \cdot \text{fatty\_acid (g/kg DM)}$$

where,

Methane is the daily methane emission from enteric fermentation in units of MJ/day. This can be converted to mass unit by using the calorific value of methane at 50.0 MJ/kg (Styles et al. 2016).
DM_intake is the daily dry matter intake in kg/day
fatty_acid is the fatty acid content of the feed ration in g/kg dry matter

Equation 3.6 cannot be used directly since it is not compatible with the used approach for calculating CH_4 from methane in IPCC (2006). Instead, the formula is applied in the Arla FarmTool v2016 on a sample of 148 farms from Denmark with data for 2017 and 2018. For this sample, the CH_4 emission per MJ gross energy (GE) feed intake is plotted against the fatty acid (FA) content of the feed ration (kg FA/kg dm). Based on this plot, see **Figure 3.1**, a linear regression function of kg CH_4/MJ GE as function of FA% is established, see **Equation 3.7**.

Equation 3.7

$$\textbf{Methane}\ (\text{kg } CH_4\text{ /MJ GE}) = \mathbf{-5.81 \cdot 10^{-5}}\ [\text{kg } CH_4/\text{MJ}^{-1}\ (\text{kg FA/MJ GE})^{-1}] \cdot \textbf{FA\%}\ [\text{kg FA/MJ GE}] + \mathbf{0.00136}\ [\text{kg } CH_4/\text{MJ}]$$

where

FA% is the actual fatty acid content of the feed ration measured on as dry matter basis

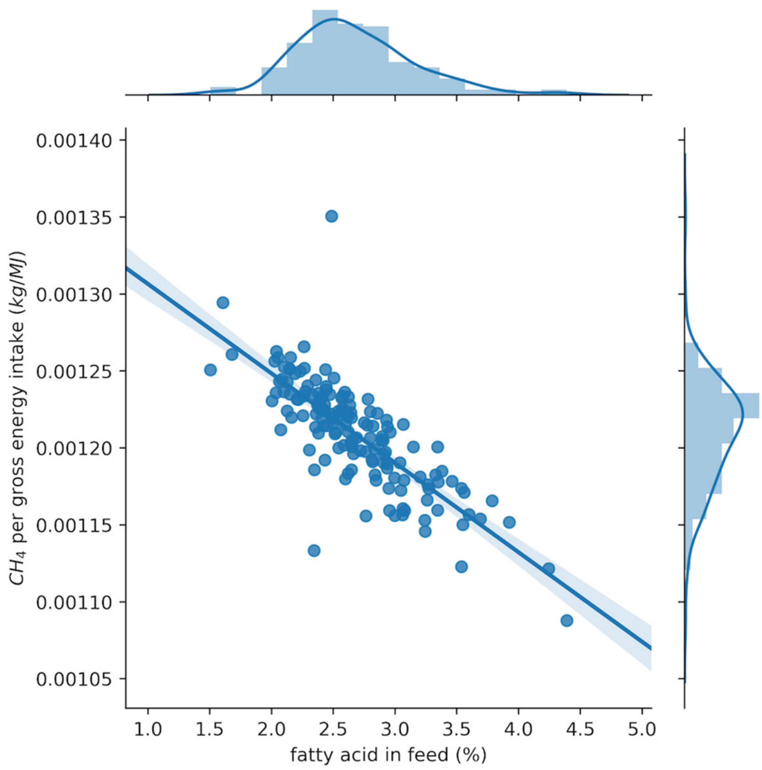

Figure 3.1. Methane from enteric fermentation per gross energy feed intake plotted against the fatty acid content in the feed ratio for a sample of 148 farms in DK in 2017 and 2018 using the FarmTool v2016.

Equation 3.7 is used to calculate an adjustment factor to the default CH_4 calculated using the IPCC (2006) approach, see Equation 3.8.

Equation 3.8

$$\text{correction\_factor} = \frac{-5.81 \cdot 10^{-5} \cdot FA\%_{actual} + 0.00136}{-5.81 \cdot 10^{-5} \cdot FA\%_{average} + 0.00136}$$

where

$FA\%_{actual}$ is the actual fatty acid content of the feed ration measured on as dry matter basis

$FA\%_{average}$ is the average fatty acid content of the feed ration in Denmark, Germany and Great Britain in 2012 at 2.61%. This has been calculated based on the feed mix in these countries based on information in Dalgaard et al. (2016).

4 FarmTool module: housing and manure storage, treatment and land application

The modelling of emissions from housing, manure storage, treatment and land application in the Arla FarmTool v2016 is described in Schmidt and Dalgaard (2012), Dalgaard and Schmidt (2012), and Dalgaard et al. (2016).

A number of technologies to mitigate emissions from housing, storage and land application are introduced in the Arla FarmTool v2021. An overview of this is presented in **Table 4.1**. Indirect effects, such as changes in indirect nitrous oxide emissions caused by reduced nitrate leaching, are included in the model, but not shown in the table.

Table 4.1. Environmental technologies.

Technology	Affected flows	Documentation
Housing systems and storage		
Acidification of slurry before storage	Use of 6 kg sulphuric acid per 1000 kg slurry. Ammonia emissions from slurry reduced by 50% in housing. Ammonia emissions from slurry tanks: 1% of applied N manure. Methane emissions from slurry reduced by 77%.	Section 4.1
	Reduced ammonia emissions in field. Increased substitution of mineral N-fertiliser by 12.5%. Increased substitution of mineral P- and K-fertiliser.	Section 4.4
Storage cover	Emissions from slurry reduced when floating or full covers are used instead of no cover. N loss is reduced from 6% to 1-2%.	Section 4.2
Anaerobic digester		
Anaerobic digestion of slurry	Shorter slurry storage time reduces methane and nitrous oxide by 41% and 100% respectively. Production of heat and electricity may substitute alternative energy.	Section 4.3
	Increased substitution of mineral fertiliser by 24%. Increased substitution of mineral P- and K-fertiliser. Reduction of nitrate leaching from field by 8%.	Section 4.3 Section 4.4
Manure land application		
Acidification of slurry before or during application to field	Use of 6 kg sulphuric acid per 1000 kg slurry. Ammonia emissions reduced by 0-49% depending on the application method. Increased substitution of mineral N-fertiliser by 12.5%. Increased substitution of mineral P- and K-fertiliser.	Section 4.4
Injection of slurry to un-cropped land	Ammonia emission from slurry 85% lower than for band spreading of slurry Nitrous oxide emissions 100% higher than for band spreading of slurry	
Injection of slurry to grass land	Ammonia emission from slurry 25% lower than for band spreading of slurry. Nitrous oxide emissions 100% higher than for band spreading of slurry	

4.1 Housing

The amounts of ammonia, methane and nitrous oxide emitted from housing do not only depend of the amount of manure excreted from the cattle, but also on the type of manure management system. The ammonia emission factors related to manure management systems in the previous version of FarmTool (version 2016) are based on Poulsen et al. (2001), as presented by Schmidt and Dalgaard (2012, p 50), whereas the methane and nitrous oxide emission factors are based on IPCC (2006), as presented by Dalgaard and Schmidt (2016, p 57). The ammonia emission factors from Poulsen et al. (2001) were revised by Kai et al. (2014), but the ammonia emission factors related to cattle manure management systems were found to be the same as those published in 2001 by Poulsen et al. (2001). Thus, the ammonia emission factors in the current version of the FarmTool are not changed. However, according to Kai (2019), it is recently found that the ammonia emission factors for two types of the housing systems (loose holdings with beds) used in the FarmTool are lower. But as these results are not yet published, they are not integrated to the current version of the FarmTool.

The List of Environmental Technologies is a list with agricultural technologies, which are tested on farms and documented to reduce the environmental impact of agricultural production (Danish Environmental Protection Agency 2019). Technologies on the list are fulfilling the criteria for Best Available Technology (DEPA 2019) and documentation is available for all users. Currently, the only technology applicable for cattle manure management systems is slurry acidification, which on the list is named 'JH acidification NH_4^+'. Formerly, scrapers were also on the list, but these are recently removed, because it has been revealed they do not reduce the ammonia emissions (Kai 2019). Therefore, the only environmental technology that will be added to the manure management system in the version 2019 of the FarmTool is slurry acidification. Based on Miljøstyrelsen (2011), it is assumed that slurry acidification decreases pH of the slurry to 5.5 -6.0, which results in 50% reduction of ammonia emission in cattle manure management system.

In the model, an average of 6.0 kg concentrated sulphuric acid per 1000 kg cattle slurry is used. For the conversion of kg N in slurry to tons slurry, it is assumed 1000 kg cattle slurry contains 5.55 kg N (Poulsen et al. 2001, table 11.7). In practice, lime is added to the acidified slurry to increase pH before it is applied to the field (Olesen et al., 2018, p 39). Olesen et al. (2018) estimates approximately 145 kg extra lime/ha/year is required if the slurry is acidified. However, this is not included, because the GHG emissions from the lime contribute less than 0.5% to the total carbon footprint of crops in a sensitivity test that was carried out in the FarmTool. For the test 145 kg lime was added to both barley, oat and rye cultivated in Denmark and the carbon footprint increased with 0.20-0.48%. A similar test was carried out with barley from the Agri-footprint database (Blonk Agri-footprint BV 2017) and it was confirmed that the contribution from lime is negligible.

The methane emissions in housing and storage from acidified cattle slurry is expected to be lower than non-acidified slurry according to Miljøstyrelsen (2011), but the reduction is not quantified in this reference. However, a 77% reduced methane emission from acidified slurry is integrated in the FarmTool. This is based on Petersen et al. (2012, p 88), who found that methane emissions can be reduced 67-87% if acid is added to cattle slurry.

When acidified slurry is applied to the field, emissions are different compared to emissions from non-acidified slurry. This is described in the section 4.4.

4.2 Manure storage

Ammonia emissions from manure storage, depends on the type of cover of the slurry tank and the type of slurry. The ammonia emission factors applied in the model are presented in **Table 4.2**. If the cattle slurry is acidified, the ammonia emission factor is 1% regardless of the cover type. When slurry is anaerobic digested, the methane and nitrous oxide emissions from storage are reduced. This is documented in the section 4.3.

Table 4.2. Ammonia emission factors used for calculation of ammonia emission from stored manure.

Type of manure and cover	Emission factor, NH_3-N as % of total N	Data source
Cattle slurry, no cover	6%	Hansen et al. (2008, table 1)
Cattle slurry, floating cover	2%	Hansen et al. (2008, table 1)
Cattle slurry, full cover	1%	Hansen et al. (2008, table 1) Miljøstyrelsen (2010c, p 1)
Acidified cattle slurry	1%	Miljøstyrelsen (2011, p 1)

4.3 Anaerobic digestion of slurry

In the 2016 version of the FarmTool, anaerobic digestion was not included as a treatment option. Anaerobic digestion of manure has several environmental effects and is therefore included in the current version. In Denmark, 96% of the anaerobically digested manure is slurry, whereas deep litter and solid manure are almost not anaerobically digested (Mikkelsen et al. 2016, p 11). In the data entry sheet of the FarmTool, it is possible to enter data as if deep litter or solid manure are anaerobically digested, but the model will calculate it as slurry.

The FarmTool differentiates between biogas treatment taking place at a centralised facility or at farm level. The scale (centralised versus on-farm) of the biogas facility affects the options to utilize the electricity and heat by-products of the treatment process.

The included effects of digestion of slurry in the FarmTool are:

- Housing and storage: Reduced methane and nitrous oxide emissions due to shorter storage times
- Anaerobic digester:
  - Reduced methane emissions because the biogas is captured in the digester
  - Part of the produced biogas (methane) is lost as leakage
  - Substituted electricity and heat, due to energy production from the produced biogas
- Transport: Transport of slurry to central anaerobic digesters
- Field: Reduced nitrate loss and increased substitution rate of mineral fertiliser

Housing and storage

Slurry which is anaerobically digested is stored for a shorter time, which results in lower emissions of methane and nitrous oxide from housing and storage compared to non-aerobic digested slurry. Mikkelsen et al. (2016, p 15) estimate that the methane conversion factor (MCF) for slurry which is anaerobically digested is 41% lower compared to non-treated slurry. The emission factor for nitrous oxide is 0 according to IPCC (2006, table 10.21). The reduced emissions from housing and storage are included in the cattle system in the model, whereas the flows related to the anaerobic digester and field application are included in the manure treatment activities described in the section 4.4. For details on distinction between cattle system and manure treatment activities, see Schmidt and Dalgaard (2012).

Digestion process

This study considers mesophilic continuously stirred anaerobic digestion, which is the most common (Hou et al. 2017). Thermophilic anaerobic digestion operates at higher temperatures and has higher methane yields, but they are also much more unstable and are relatively rare. The anaerobic digester receives organic material, and through a series of reactions of hydrolysis, fermentation, acetogenesis and methanogenesis, a fraction of the volatile solids is processed into CH_4, CO_2 and H_2O. The process requires electricity for stirring the digestate and heat to keep the mix at around 35^{o} C. At lower temperatures, the biological reactions taking place in the digestor would slow down the biological reactions.

Methane yield and energy production

Methane yields are very dependent on the type of feedstock used. Slurry has a relatively low methane yield since it has already been “digested”. Cattle manure has a high amount of inorganic compounds and fibres not digested by cattle (Nasir et al., 2012). Although slurry could be mixed with other feedstock to improve yields, this study only accounts the biogas from the manure because this is what is related to milk production.

Utilisation of heat and electricity

Biogas from the anaerobic digestion is often burned in a CHP plant providing electricity and heat. Electricity is always used and a percentage of the heat not used in the anaerobic digester can substitute other sources of heat. Studies analysing the potential of heat from the CHP unit in biogas plants have found that there is a lack of reliable data on heat utilization in many countries (Ramanauskaite et al. 2012) and that status of heat utilization is "not satisfactory".

The percentage of heat not utilised is highly dependent on country-specific incentives and plant conditions. For instance, all centralised Danish plants were connected to district heating, although they have a heat surplus in summer (Ramanauskaite et al. 2012). A survey of German facilities found that 43% of the heat was being used to substitute other sources of heat (Ramanauskaite et al. 2012). None of the heat was used in large scale from UK farms (Styles et al. 2016). For Denmark it is known that all centralised facilities are connected to district heating, therefore, in that case heat production in CHP units will displace heat produced by district heating systems, though there may be surplus during the summer (Mergner et al. 2013). Based on this, it has been assumed that 80% of the heat is utilised. No data are identified for Sweden, and therefore the same degree of utilisation has been assumed. The type of heat replaced is based on country-specific IEA statistics of energy use by the agricultural sector (section on Energy by-products) unless better information is available.

Table 4.3 summarises the parameters used in the calculation of centralised anaerobic digesters. For on-farm facilities, the amount of heat effectively utilised is approximated by the response of the farmers.

Table 4.3. Characteristics of anaerobic digestion process of cattle manure.

Parameter	Unit	Amount	Reference
CH_4 yield and energy generation			
Electric efficiency	%	35%	(Styles et al., 2016)
Heat efficiency	%	45%	(Styles et al., 2016)
Methane yield	m^3 CH4/t DM	140	(Styles et al., 2016)
Methane calorific value (LHV)	MJ/kg	50	(Styles et al., 2016)
Methane density	kg/ Nm^3	0.67	(Styles et al., 2016) (ideal gas equation)
Methane losses	%	1%	(Styles et al., 2016)
Digestate			
Digestate NH4-N/total-N	NH4-N/total-N	75%	(Styles et al., 2016)
Energy requirement			
Parasitic heat demand	Heat used / heat produced	33%	(Styles et al., 2016)
Parasitic electricity demand	kWh used/kWh produced	6%	(Styles et al., 2016)
Heat utilisation			
DK – centralised	%	80%	(Mergner et al. 2013)
DE – centralised	%	43%	(Ramanauskaite et al. 2012)
SE – centralised	%	80%	Assumed to be as in Denmark
UK – centralised	%	0%	(Styles et al. 2016)
Farm plant	%	0%	Estimated
Electricity utilisation			
Centralised	%	100%	Assumed
Farm plant	%	100%	Assumed

4.4 Land application of manure

After the manure leaves the storage or anaerobic digester, it can be treated in different ways. In the FarmTool v2016, there are six different versions of manure treatment/land application activities (Dalgaard and Schmidt 2012, table 3.13). In the current v2021, these are extended to 27 and include different combinations of the following technologies:

- Land application of acidified slurry, which in general leads to reduced ammonia and nitrous oxide emissions, but also requires input of acid.
- Field application methods, which affects the availability of nitrogen and emissions of nitrate, ammonia, nitrous oxide. The four application methods included in the modelling are illustrated in **Figure 4.1** and include:
  - Injection, uncropped land
  - Injection, grass land
  - Band spreading
  - Broad spreading
- Anaerobic digested slurry, which substitutes fossil energy. Type and amount of substituted energy depend on the country, and whether it is a farm scale or central plant. In the field, anaerobically digested slurry substitutes more mineral fertiliser than untreated slurry, and it contributes to reduced nitrate leaching.

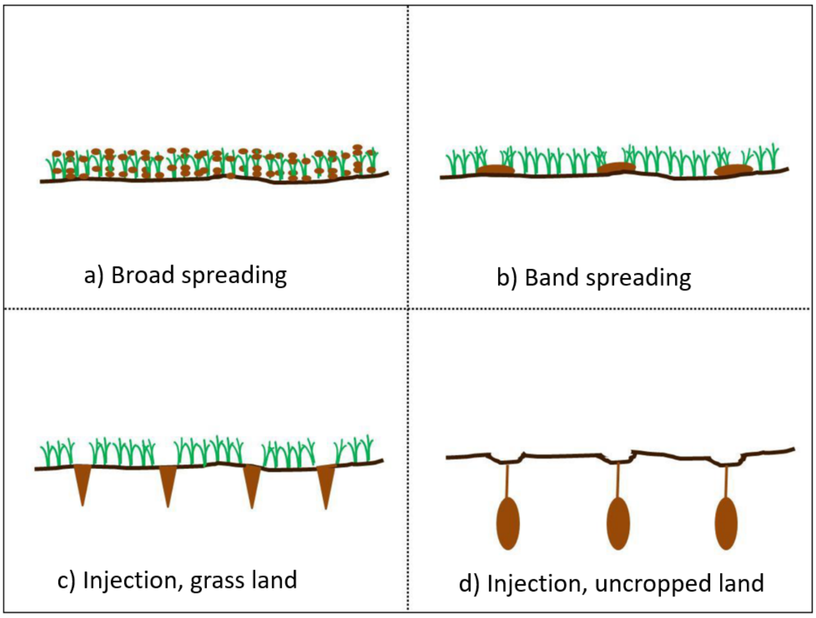

Figure 4.1. Techniques used for application of slurry to fields. Obtained from Birkmose (2014).

Land application of manure is fully linked to the animals producing the manure. I.e. using manure on crops have the same effect as using mineral fertiliser (corrected for the fertiliser effect of the manure).

The manure land application activities are modelled as 'treatment activities'. When manure is applied to land, the use of mineral fertiliser can be used accordingly – in a specified proportion. The application of manure, which is a by-product from milk and meat production, results in displacement of mineral fertiliser, which reduces the GHG emissions related to the production of mineral fertiliser. On the other hand, the ammonia and nitrous oxide emissions from utilization of slurry are higher per kg applied N compared to the emissions from the application of mineral fertiliser, and this increases the ammonia and nitrous oxide emitted per kg milk produced. This is further described in Schmidt and Dalgaard (2012).

The emissions in the lower parts of **Table 4.7** and **Table 4.8** are calculated following the procedures presented by Schmidt and Dalgaard (2012) and Dalgaard et al. (2012). These procedures are to a large extend based on IPCC (2006). The methane emitted from land application of manure is calculated as part of the cattle system according to IPCC (2006, p 10-35), as it has not been possible to identify methane conversions factor.

In several cases more detailed ammonia, nitrate and nitrous oxide emission factors, than those published by IPCC (2006) are used. This is described in the following.

The ammonia emission factors used for land applied manure are presented in **Table 4.4**.

Table 4.4. Ammonia emission factors for different kinds of land applied manure.

Manure and form of application	% of NH_4-N lost as NH_3-N	Data source
Slurry, band spreading	31.8%	Hansen et al. (2008, table 10)
Slurry (acidified), band spreading	16.2%	VERA (2012, p 1)
Slurry, injection uncropped land	4.8%	Miljøstyrelsen (2010a, p 1)
Slurry (acidified), injection uncropped land	4.8%	Toft (2019)
Slurry, injection grass land	23.9%	Miljøstyrelsen (2010b, p 1)
Slurry (acidified), injection grass land	12.5%	Seidel et al. (2017, p 27)
Slurry, broad spreading	40.6%	Hansen et al. (2008, p 24-25)
Slurry (acidified), broad spreading	20.7%	Toft (2019)
Solid/deep litter	48.0%	Hansen et al. (2008, table 15)

It is assumed 58.1% of the nitrogen in cattle slurry is ammonium (NH_4-N) (Hansen et al., table 8). The ammonia emission factor for 'Slurry, band spreading' is calculated as average of cattle slurry applied to uncropped land and land with crops (Hansen et al. 2008, table 10). According to VERA (2012, p 1) the ammonia emission from band spreading can be reduced by 49% if the cattle slurry continuously is mixed with concentrated sulphuric acid. The technology tested by VERA (2012) is named SyreN and manufactured by BioCover a/s. There are also other technologies on the market, but they are not used in the model. According to Toft (2019), addition of sulphuric acids to slurry, which is injected on uncropped land, does not reduce the ammonia emissions. Therefore, the ammonia emission factors for 'Slurry, injection uncropped land' and 'Slurry (acidified), injection uncropped land' are equal. It is assumed that acidification of slurry also reduces the ammonia emissions with 49% (100% - 20.7%/40.6%), when it is added to slurry, which is applied to the field by broad spreading.

The List of Environmental Technologies (DEPA 2019), amongst other technologies, includes slurry injection to uncropped land and slurry injection to grass land. Compared to band spreading, the ammonia emission factors for these two slurry injections technologies are 85% and 25% lower (Miljøstyrelsen 2010a, 2010b). Compared to band spreading, the diesel use is higher for injection. The changes in diesel consumption are accounted for directly, since these data are directly entered in the model.

Slurry injected to grass land can also be acidified. According to Seidel et al. (2017, p 27), this can reduce the ammonia emission by 42.2-79.4%, depending on the amount of sulphuric acid added. In the current model, an average of the upper and lower values (=60.8) is used. Broad spreading is banned in several countries, because it has a high ammonia emission factor, compared to other available slurry application technology. According to

Hansen et al. (2008, p 24-25) the ammonia emission is approximately 1.7 times higher than the emission from band spreading and this is also included in the current version of the model.

The amount of ammonia loss from anaerobic digested slurry depends on several parameters. The pH of slurry increases after it is anaerobic digested and this results in increased risk of ammonia emission. However, anaerobic digestion also reduces the dry matter content of slurry, which results in faster incorporation of slurry in to the soil and thereby lower the risk of ammonia loss. (Sørensen and Børgesen 2015, p 20). Whether the effect of increased pH or faster soil incorporation is dominating depends amongst other parameters on application methods and weather. In the current model it is assumed, that anaerobic digestion of slurry does not affect the total ammonia emission from slurry applied to fields. This assumption is in accordance with Sørensen and Børgesen (2015, p 20) and Hansen et al. (2008).

The emission factors for nitrate leaching and nitrous oxide are from IPCC (2006), but with the following two exceptions.

- The nitrate leaching can be reduced by 1.5 – 3.1 kg N per 100 kg slurry-N applied over a time horizon of 50 years, if the slurry is anaerobically digested (Sørensen et al. 2015, p 40, 22-23). In the current model an average value (=2.30 kg N per 100 kg slurry-N) of the interval is used. According to IPCC (2006, table 11.3), 30 kg N per 100 kg slurry-N is leached and thereby the application of anaerobically digested slurry can reduce the leaching with 7.7% (=2.3/30). This also affects the indirect emission of nitrous oxide (Dalgaard et al. 2012).
- Injection of slurry compared to slurry band spreading increases the nitrous oxide by 100% (Miljøstyrelsen 2010a, 2010b).

A detailed summary of the calculation of N emissions is presented in **Table 4.5** to **Table 4.9**. The N emissions are identical for manure regardless if it is anaerobically digested in farm plant or central plant, and therefore these N emissions are presented together in **Table 4.7** and **Table 4.8**.

Table 4.5. Calculation of N emissions from manure treatment activities without anaerobic digestion. Reference product is 1 kg N in manure.

Technology mix					
Type of manure		Slurry	Slurry	Slurry	Slurry
Anaerobic digested		-	-	-	-
Acidified		-	+	-	+
Application method		Injection uncropped land	Injection uncropped land	Injection grass land	Injection grass land
Flows	**Unit**				
Applied manure					
Manure, N	kg N	1	1	1	1
Nitrous oxide (direct)					
From manure	kg N	0.0200	0.0200	0.0200	0.0200
From displaced fertiliser	kg N	-0.0070	-0.0079	-0.0070	-0.0079
From manure treatment	kg N	0.0130	0.0121	0.0130	0.0121
Ammonia					
From manure	kg N	0.0277	0.0277	0.1387	0.0725
From displaced fertiliser	kg N	-0.0140	-0.0158	-0.0140	-0.0158
From manure treatment	kg N	0.0137	0.0120	0.1247	0.0567
Nitrate					
From manure	kg N	0.3000	0.3000	0.3000	0.3000
From displaced fertiliser	kg N	-0.2100	-0.2363	-0.2100	-0.2363
From manure treatment	kg N	0.0900	0.0638	0.0900	0.0638
Nitrous oxide (indirect)					
From manure	kg N	0.0026	0.0026	0.0039	0.0031
From displaced fertiliser	kg N	-0.0017	-0.0020	-0.0017	-0.0020
From manure treatment	kg N	0.0008	0.0006	0.0021	0.0011
Summary of N emissions					
Nitrous oxide (direct)	kg N_20	0.0204	0.0191	0.0204	0.0191
Nitrous oxide (indirect)	kg N_20	0.0071	0.0048	0.0071	0.0048
Ammonia	kg NH_3	0.0167	0.0146	0.1514	0.0689
Nitrate	kg NO_3	0.3986	0.2823	0.3986	0.2823

Table 4.6. Calculation of N emissions from manure treatment activities without anaerobic digestion. Reference product is 1 kg N in manure.

Technology mix					
Type of manure		Slurry	Slurry	Slurry	Slurry
Anaerobic digested		-	-	-	-
Acidified		-	+	-	+
Application method		Band spreading	Band spreading	Broad spreading	Broad spreading
Flows	**Unit**				
Applied manure					
Manure, N	kg N	1	1	1	1
Nitrous oxide (direct)					
From manure	kg N	0.0100	0.0100	0.0100	0.0100
From displaced fertiliser	kg N	-0.0070	-0.0079	-0.0070	-0.0079
From manure treatment	kg N	0.0030	0.0021	0.0030	0.0021
Ammonia					
From manure	kg N	0.1849	0.0943	0.2357	0.1202
From displaced fertiliser	kg N	-0.0140	-0.0158	-0.0140	-0.0158
From manure treatment	kg N	0.1709	0.0785	0.2217	0.1045
Nitrate					
From manure	kg N	0.3000	0.3000	0.3000	0.3000
From displaced fertiliser	kg N	-0.2100	-0.2363	-0.2100	-0.2363
From manure treatment	kg N	0.0900	0.0638	0.0900	0.0638
Nitrous oxide (indirect)					
From manure	kg N	0.0044	0.0034	0.0050	0.0037
From displaced fertiliser	kg N	-0.0017	-0.0020	-0.0017	-0.0020
From manure treatment	kg N	0.0027	0.0014	0.0033	0.0017
Summary of N emissions					
Nitrous oxide (direct)	kg N_20	0.0047	0.0033	0.0047	0.0033
Nitrous oxide (indirect)	kg N_20	0.0027	0.0014	0.0033	0.0017
Ammonia	kg NH_3	0.2075	0.0954	0.2693	0.1269
Nitrate	kg NO_3	0.3986	0.2823	0.3986	0.2823

Table 4.7. Calculation of N emissions from manure treatment activities with anaerobic digestion. Reference product is 1 kg N in manure.

Technology mix					
Type of manure		Slurry	Slurry	Slurry	Slurry
Anaerobic digested		Farm/central plant	Farm/central plant	Farm/central plant	Farm/central plant
Acidified		-	+	-	+
Application method		Injection uncropped land	Injection uncropped land	Injection grass land	Injection grass land
Flows	**Unit**				
Applied manure					
Manure, N	kg N	1	1	1	1
Nitrous oxide (direct)					
From manure	kg N	0.0200	0.0200	0.0200	0.0200
From displaced fertiliser	kg N	-0.0087	-0.0087	-0.0087	-0.0087
From manure treatment	kg N	0.0113	0.0113	0.0113	0.0113
Ammonia					
From manure	kg N	0.0277	0.0277	0.1387	0.0725
From displaced fertiliser	kg N	-0.0173	-0.0173	-0.0173	-0.0173
From manure treatment	kg N	0.0104	0.0104	0.1214	0.0552
Nitrate					
From manure	kg N	0.2233	0.2233	0.2233	0.2233
From displaced fertiliser	kg N	-0.2595	-0.2595	-0.2595	-0.2595
From manure treatment	kg N	-0.0362	-0.0362	-0.0362	-0.0362
Nitrous oxide (indirect)					
From manure	kg N	0.0020	0.0020	0.0033	0.0025
From displaced fertiliser	kg N	-0.0021	-0.0021	-0.0021	-0.0021
From manure treatment	kg N	-0.0001	-0.0001	0.0012	0.0004
Summary of N emissions					
Nitrous oxide (direct)	kg N_20	0.0178	0.0178	0.0178	0.0178
Nitrous oxide (indirect)	kg N_20	0.0056	0.0034	0.0056	0.0034
Ammonia	kg NH_3	0.0127	0.0127	0.1474	0.0670
Nitrate	kg NO_3	-0.1602	-0.1602	-0.1602	-0.1602

Table 4.8. Calculation of N emissions from manure treatment activities with anaerobic digestion. Reference product is 1 kg N in manure.

Technology mix					
Type of manure		Slurry	Slurry	Slurry	Slurry
Anaerobic digested		Farm/central plant	Farm/central plant	Farm/central plant	Farm/central plant
Acidified		-	+	-	+
Application method		Band spreading	Band spreading	Broad spreading	Broad spreading
Flows	**Unit**				
Applied manure					
Manure, N	kg N	1	1	1	1
Nitrous oxide (direct)					
From manure	kg N	0.0100	0.0100	0.0100	0.0100
From displaced fertiliser	kg N	-0.0087	-0.0087	-0.0087	-0.0087
From manure treatment	kg N	0.0013	0.0013	0.0013	0.0013
Ammonia					
From manure	kg N	0.1849	0.0943	0.2357	0.1202
From displaced fertiliser	kg N	-0.0173	-0.0173	-0.0173	-0.0173
From manure treatment	kg N	0.1676	0.0770	0.2184	0.1029
Nitrate					
From manure	kg N	0.2233	0.2233	0.2233	0.2233
From displaced fertiliser	kg N	-0.2595	-0.2595	-0.2595	-0.2595
From manure treatment	kg N	-0.0362	-0.0362	-0.0362	-0.0362
Nitrous oxide (indirect)					
From manure	kg N	0.0039	0.0028	0.0044	0.0031
From displaced fertiliser	kg N	-0.0021	-0.0021	-0.0021	-0.0021
From manure treatment	kg N	0.0017	0.0006	0.0023	0.0009
Summary of N emissions					
Nitrous oxide (direct)	kg N_20	0.0021	0.0021	0.0021	0.0021
Nitrous oxide (indirect)	kg N_20	0.0017	0.0006	0.0023	0.0009
Ammonia	kg NH_3	0.2035	0.0935	0.2652	0.1250
Nitrate	kg NO_3	-0.1602	-0.1602	-0.1602	-0.1602

Table 4.9. Calculation of N emissions from manure treatment activities without anaerobic digestion. Reference product is 1 kg N in manure.

Technology mix				
Type of manure		Solid	Deep litter	Liquid/solid
Anaerobic digested		-	-	-
Acidified		-	-	+
Application method		Not specified	Not specified	Deposited by grazing cattle
Flows	**Unit**			
Applied manure				
Manure, N	kg N	1	1	1
Nitrous oxide (direct)				
From manure	kg N	0.0100	0.0100	0.0200
From displaced fertiliser	kg N	-0.0065	-0.0045	-0.0065
From manure treatment	kg N	0.0035	0.0055	0.0135
Ammonia				
From manure	kg N	0.2788	0.2788	0.0700
From displaced fertiliser	kg N	-0.0130	-0.0090	-0.0130
From manure treatment	kg N	0.2658	0.2698	0.0570
Nitrate				
From manure	kg N	0.3000	0.3000	0.3000
From displaced fertiliser	kg N	-0.1950	-0.1350	-0.1950
From manure treatment	kg N	0.1050	0.1650	0.1050
Nitrous oxide (indirect)				
From manure	kg N	0.0055	0.0055	0.0031
From displaced fertiliser	kg N	-0.0016	-0.0011	-0.0016
From manure treatment	kg N	0.0039	0.0044	0.0015
Summary of N emissions				
Nitrous oxide (direct)	kg N_20	0.0055	0.0086	0.0212
Nitrous oxide (indirect)	kg N_20	0.0041	0.0045	0.0015
Ammonia	kg NH_3	0.3228	0.3276	0.0692
Nitrate	kg NO_3	0.4650	0.7307	0.4650

Substituted mineral fertiliser

The amount of N fertiliser substituted by non-anaerobically digested slurry, solid and deep litter is modelled with the procedure described by Dalgaard et al. (2012) and with data from Plantedirektoratet (2011, p 41).

Based on Miljøstyrelsen (2011, p 1), it is assumed that acidified slurry has a 12.5% higher nitrogen efficiency compared to non-acidified slurry. Consequently, it is modelled that 1 kg N in acidified slurry substitutes 0.788 kg mineral fertiliser (which can be compared with 0.7 for non-acidified slurry).

According to results obtained by Sørensen et al. (2012) and Sørensen and Børgesen (2015 p 32), the mineral fertiliser N replacement values are higher for anaerobic digested cattle slurry compared to non-anaerobic digested cattle slurry. Based on these results, it is estimated in the current model, that anaerobic digested slurry in general substitutes 23.6% more N mineral fertiliser than non- aerobic digested slurry. The replacement rates of P and K mineral fertiliser are calculated from the displaced N mineral fertiliser by use of P/N and K/N ratios for cattle manure from Poulsen et al. (2001, table 11.7-11.10). For further details, see Dalgaard et al. (2012, p 36-37).

Energy and material use for manure treatment

Diesel use for application of different manure types and mineral fertiliser to the field is calculated from Odderskær (2016, p 119) by using data on litre diesel used for application of 1 ton manure or application of mineral fertiliser to one hectare. Values on nitrogen contents in slurry, solid and deep litter are from Poulsen et al. (2001, table 11.7-11.10). For acidification 6 kg sulphuric acid (100%) is used per 1000 kg slurry

(Miljøstyrelsen 2011, p 2).

4.5 Summary of the LCI of environmental technologies

The life cycle inventory of the manure treatment activities is presented in **Table 4.10** to **Table 4.16**. The first six tables (**Table 4.10** to **Table 4.15**) present data for treatment of slurry and the last table (**Table 4.16**) presents data on treatment of solid, deep litter and manure deposited directly on the fields by grassing cattle. More detailed data on calculation of N emissions are presented in **Table 4.5** to **Table 4.9**, where the emissions are divided into emissions from application of slurry and avoided emissions due to substituted mineral fertiliser respectively.

The reference flow of all the LCA activities presented in the following tables is 1 kg N in manure. The by-products from the manure treatment are displaced application of mineral fertilisers (N, P and K) and energy (electricity and heat).

Table 4.10. Manure treatment activities without anaerobic digestion. Reference product is 1 kg N in manure.

Technology mix					
Type of manure		Slurry	Slurry	Slurry	Slurry
Anaerobic digested		-	-	-	-
Acidified		-	+	-	+
Application method		Injection uncropped land	Injection uncropped land	Injection grass land	Injection grass land
Flows	**Unit**				
Output of products					
Reference flow					
Manure for treatment	kg N	1	1	1	1
By-products					
Market for N-fertiliser	kg N	-0.700	-0.788	-0.700	-0.788
P-fert: TSP	kg P	-0.288	-0.323	-0.288	-0.323
K-fert: KCl	kg K	-0.796	-0.895	-0.796	-0.895
Electricity	kWh				
Heat	MJ				
Input of products					
Diesel	MJ	1.54	1.49	1.54	1.49
Sulphuric acid (100%)	kg		0.174		0.174
Emissions					
Nitrous oxide (direct)	kg N_2O	0.0204	0.0191	0.0204	0.0191
Nitrous oxide (indirect)	kg N_2O	0.0071	0.0048	0.0071	0.0048
Ammonia	kg NH_3	0.0167	0.0146	0.1514	0.0689
Nitrate	kg NO_3	0.3986	0.2823	0.3986	0.2823

Table 4.11. Manure treatment activities without anaerobic digestion. Reference product is 1 kg N in manure.

Technology mix					
Type of manure		Slurry	Slurry	Slurry	Slurry
Anaerobic digested		-	-	-	-
Acidified		-	+	-	+
Application method		Band spreading	Band spreading	Broad spreading	Broad spreading
Flows	**Unit**				
Output of products					
Reference flow					
Manure for treatment	kg N	1	1	1	1
By-products					
Market for N-fertiliser	kg N	0.700	0.788	0.700	0.788
P-fert: TSP	kg P	0.288	0.323	0.288	0.323
K-fert: KCl	kg K	0.796	0.895	0.796	0.895
Electricity	kWh				
Heat	MJ				
Input of products					
Diesel	MJ	1.54	1.49	1.54	1.49
Sulphuric acid (100%)	kg		0.174		0.174
Emissions					
Nitrous oxide (direct)	kg N_20	0.0047	0.0033	0.0047	0.0033
Nitrous oxide (indirect)	kg N_20	0.0027	0.0014	0.0033	0.0017
Ammonia	kg NH_3	0.2075	0.0954	0.2693	0.1269
Nitrate	kg NO_3	0.3986	0.2823	0.3986	0.2823

Table 4.12. Manure treatment activities with anaerobic digestion at farm plant. Reference product is 1 kg N in manure.

Technology mix					
Type of manure		Slurry	Slurry	Slurry	Slurry
Anaerobic digested		Farm plant	Farm plant	Farm plant	Farm plant
Acidified		-	+	-	+
Application method		Injection uncropped land	Injection uncropped land	Injection grass land	Injection grass land
Flows	**Unit**				
Output of products					
Reference flow					
Manure for treatment	kg N	1	1	1	1
By-products					
Market for N-fertiliser	kg N	0.865	0.865	0.865	0.865
P-fert: TSP	kg P	0.355	0.355	0.355	0.355
K-fert: KCl	kg K	0.984	0.984	0.984	0.984
Electricity	kWh	1.56	1.56	1.56	1.56
Heat	MJ				
Input of products					
Diesel	MJ	1.44	1.44	1.44	1.44
Sulphuric acid (100%)	kg		0.174		0.174
Emissions					
Nitrous oxide (direct)	kg N_20	0.0178	0.0178	0.0178	0.0178
Nitrous oxide (indirect)	kg N_20	0.0056	0.0034	0.0056	0.0034
Ammonia	kg NH_3	0.0127	0.0127	0.1474	0.0670
Nitrate	kg NO_3	-0.1602	-0.1602	-0.1602	-0.1602

Table 4.13. Manure treatment activities with anaerobic digestion at farm plant. Reference product is 1 kg N in manure.

Technology mix					
Type of manure		Slurry	Slurry	Slurry	Slurry
Anaerobic digested		Farm plant	Farm plant	Farm plant	Farm plant
Acidified		-	+	-	+
Application method		Band spreading	Band spreading	Broad spreading	Broad spreading
Flows	**Unit**				
Output of products					
Reference flow					
Manure for treatment	kg N	1	1	1	1
By-products					
Market for N-fertiliser	kg N	-0.865	-0.865	-0.865	-0.865
P-fert: TSP	kg P	-0.355	-0.355	-0.355	-0.355
K-fert: KCl	kg K	-0.984	-0.984	-0.984	-0.984
Electricity	kWh	1.56	1.56	1.56	1.56
Heat	MJ				
Input of products					
Diesel	MJ	1.44	1.44	1.44	1.44
Sulphuric acid (100%)	kg		0.174		0.174
Emissions					
Nitrous oxide (direct)	kg N_20	0.0021	0.0021	0.0021	0.0021
Nitrous oxide (indirect)	kg N_20	0.0017	0.0006	0.0023	0.0009
Ammonia	kg NH_3	0.2035	0.0935	0.2652	0.1250
Nitrate	kg NO_3	-0.1602	-0.1602	-0.1602	-0.1602

Table 4.14. Manure treatment activities with anaerobic digestion at central plant. Reference product is 1 kg N in manure.

Technology mix					
Type of manure		Slurry	Slurry	Slurry	Slurry
Anaerobic digested		Central plant	Central plant	Central plant	Central plant
Acidified		-	+	-	+
Application method		Injection uncropped land	Injection uncropped land	Injection grass land	Injection grass land
Flows	**Unit**				
Output of products					
Reference flow					
Manure for treatment	kg N	1	1	1	1
By-products					
Market for N-fertiliser	kg N	-0.865	-0.865	-0.865	-0.865
P-fert: TSP	kg P	-0.355	-0.355	-0.355	-0.355
K-fert: KCl	kg K	-0.984	-0.984	-0.984	-0.984
Electricity	kWh	1.56	1.56	1.56	1.56
Heat	MJ	18.5*util_factor[1]	18.5*util_factor[1]	18.5*util_factor[1]	18.5*util_factor[1]
Input of products					
Diesel	MJ	1.44	1.44	1.44	1.44
Sulphuric acid (100%)	kg		0.174		0.174
Emissions					
Nitrous oxide (direct)	kg N_20	0.0178	0.0178	0.0178	0.0178
Nitrous oxide (indirect)	kg N_20	0.0056	0.0034	0.0056	0.0034
Ammonia	kg NH_3	0.0127	0.0127	0.1474	0.0670
Nitrate	kg NO_3	-0.1602	-0.1602	-0.1602	-0.1602

(1) util_factor refers to the degree of utilization of heat. This differs for different countries, see **Table 4.3**.

Table 4.15. Manure treatment activities with anaerobic digestion at central plant. Reference product is 1 kg N in manure.

Technology mix					
Type of manure		Slurry	Slurry	Slurry	Slurry
Anaerobic digested		Central plant	Central plant	Central plant	Central plant
Acidified		-	+	-	+
Application method		Band spreading	Band spreading	Broad spreading	Broad spreading
Flows	**Unit**				
Output of products					
Reference flow					
Manure for treatment	kg N	1	1	1	1
By-products					
Market for N-fertiliser	kg N	-0.865	-0.865	-0.865	-0.865
P-fert: TSP	kg P	-0.355	-0.355	-0.355	-0.355
K-fert: KCl	kg K	-0.984	-0.984	-0.984	-0.984
Electricity	kWh	1.56	1.56	1.56	1.56
Heat	MJ	18.5*util_factor[1]	18.5*util_factor[1]	18.5*util_factor[1]	18.5*util_factor[1]
Input of products					
Diesel	MJ	1.44	1.44	1.44	1.44
Sulphuric acid (100%)	kg		0.174		0.174
Emissions					
Nitrous oxide (direct)	kg N_2O	0.0021	0.0021	0.0021	0.0021
Nitrous oxide (indirect)	kg N_2O	0.0017	0.0006	0.0023	0.0009
Ammonia	kg NH_3	0.2035	0.0935	0.2652	0.1250
Nitrate	kg NO_3	-0.1602	-0.1602	-0.1602	-0.1602

(1) util_factor refers to the degree of utilization of heat. This differs for different countries, see **Table 4.3**.

Table 4.16. Manure treatment activities without anaerobic digestion. Reference product is 1 kg N in manure.

Technology mix				
Type of manure		Solid	Deep litter	Liquid/solid
Anaerobic digested		-	-	-
Acidified		-	-	-
Application method		Not specified	Not specified	Deposited by grazing cattle
Flows	**Unit**			
Output of products				
Reference flow				
Manure for treatment	kg N	1	1	1
By-products				
Market for N-fertiliser	kg N	-0.650	-0.450	-0.650
P-fert: TSP	kg P	-0.267	-0.242	-0.267
K-fert: KCl	kg K	-0.739	-0.636	-0.739
Electricity	kWh			
Heat	MJ			
Input of products				
Diesel	MJ	3.31	2.58	
Sulphuric acid (100%)	kg			
Emissions				
Nitrous oxide (direct)	kg N_2O	0.0055	0.0086	0.0212
Nitrous oxide (indirect)	kg N_2O	0.0041	0.0045	0.0015
Ammonia	kg NH_3	0.3228	0.3276	0.0692
Nitrate	kg NO_3	0.4650	0.7307	0.4650

5 FarmTool module: crop cultivation

The modelling of emissions and inputs to crop cultivation activities in the Arla FarmTool v2016 is described in Schmidt and Dalgaard (2012), Dalgaard and Schmidt (2012), and Dalgaard et al. (2016). In the FarmTool v2021, the emission factors for organic soils (peat soils) are updated. This is described in the section below.

5.1 Organic soils

Organic soils are modelled by using the most recent available data available in national inventory reports from DE, DK, SE and UK submitted under the UNFCCC (2019).

The applied data are presented in **Table 5.1**.

Table 5.1. Emission factors for drained cultivated organic soils (UNFCCC 2019).

	Cropland		Grassland	
Country	kg CO_2 ha^{-1}	kg N_2O ha^{-1}	kg CO_2 ha^{-1}	kg N_2O ha^{-1}
DE	29,700	16.8	27,133	4.24
DK	42,167	20.4	30,800	6.76
SE	22,367	20.4	9,533	4.40
UK	28,967	20.4	19,433	6.76

6 FarmTool module: Feed

The modelling of feed in the Arla FarmTool v2016 is described in Schmidt and Dalgaard (2012), Dalgaard and Schmidt (2012), and Dalgaard et al. (2016). In the FarmTool v2021, a number of new features are implemented. This includes:

- Option for modifying the composition of standard mixes of purchased feed: it can now be specified whether the concentrate is soy-containing/soy-free and the crude protein content can be specified.
- New types of purchased feed are added to the tool.

The above mentioned new features are described in the following.

6.1 Purchased concentrates and option for specifications

Most often the actual mix of feed in purchased concentrates is not known. Therefore, the model operates with default mixes for each country, see **Table 6.2** to **Table 6.5**. The mixes are obtained based on information from Arla Foods.

When the FarmTool is used at the farm level, the user specify:

- kg of low protein concentrate
  - soy-containing
  - soy-free
- kg of high protein concentrate
  - soy-containing
  - soy-free
- crude protein content of
  - low protein concentrate
  - high protein concentrate

Based on the specified crude protein content above, the default mixes for each country are modified so that the resulting crude protein matches with what is specified. This is done by dividing the mix into two groups of feed components: High protein and low protein components. The relative share within each mix is kept constant, while the quantity of each mix is adjusted to meet the specified crude protein content.

Further, for soy-free concentrate, soybean meal in the default mix is set to zero, while the high and low groups are adjusted to meet the specified protein content.

Table 6.1: Division of the feed components into two groups of components: high protein and low protein.

Feed in concentrate	High/low protein
Barley	Low
Wheat	Low
Broad beans	Low
Maize grain	Low
Soybean meal	High
Rapeseed meal	High
Sunflower cake	High
Beet pulp, dried (DM=89%)	Low
Molasses	Low
Palm oil (fats)	Low
Palm kernel meal	Low
Wheat husk	Low
Brewer's grain (DM=90%)	High
Feed urea	High
Mineral salts etc.	Low

Table 6.2: Default mix of concentrates **Germany**. The contents are shown on dry matter basis.

	Low protein		High protein	
Feed in concentrate	**Soy-containing**	**Soy-free**	**Soy-containing**	**Soy-free**
Barley	0%	6%	1%	0%
Wheat	0%	6%	1%	0%
Broad beans	0%	5%	0%	0%
Maize grain	41%	25%	0%	0%
Soybean meal	20%	0%	25%	0%
Rapeseed meal	20%	34%	72%	85%
Sunflower cake	0%	3%	0%	0%
Beet pulp, dried (DM=89%)	15%	9%	0%	10%
Molasses	3%	3%	1%	1%
Palm oil (fats)	0%	0%	0%	0%
Palm kernel meal	0%	0%	0%	0%
Wheat husk	0%	5%	0%	0%
Brewer's grain (DM=90%)	0%	4%	0%	2%
Feed urea	0%	0%	0%	2%
Mineral salts etc.	1%	2%	0%	0%
Total	**100%**	**100%**	**100%**	**100%**

Table 6.3: Default mix of concentrates **Denmark**. The contents are shown on dry matter basis.

Feed in concentrate	Low protein		High protein	
	Soy-containing	Soy-free	Soy-containing	Soy-free
Barley	8%	10%	12%	10%
Wheat	8%	10%	12%	10%
Broad beans	0%	0%	0%	0%
Maize grain	2%	0%	0%	5%
Soybean meal	5%	0%	6%	0%
Rapeseed meal	6%	15%	25%	25%
Sunflower cake	8%	10%	0%	25%
Beet pulp, dried (DM=89%)	23%	28%	0%	1%
Molasses	2%	1%	0%	0%
Palm oil (fats)	1%	1%	1%	3%
Palm kernel meal	0%	0%	0%	0%
Wheat husk	16%	10%	16%	0%
Brewer's grain (DM=90%)	20%	15%	25%	20%
Feed urea	0%	0%	3%	2%
Mineral salts etc.	0%	1%	0%	0%
Total	**100%**	**100%**	**100%**	**100%**

Table 6.4: Default mix of concentrates **Sweden**. The contents are shown on dry matter basis.

Feed in concentrate	Low protein		High protein	
	Soy-containing	Soy-free	Soy-containing	Soy-free
Barley	22%	22%	0%	0%
Wheat	22%	22%	0%	0%
Broad beans	0%	0%	30%	30%
Maize grain	4%	4%	0%	0%
Soybean meal	5%	0%	8%	0%
Rapeseed meal	29%	34%	50%	50%
Sunflower cake	0%	0%	0%	0%
Beet pulp, dried (DM=89%)	2%	2%	0%	0%
Molasses	3%	3%	0%	0%
Palm oil (fats)	2%	2%	6%	6%
Palm kernel meal	0%	0%	0%	0%
Wheat husk	7%	7%	0%	0%
Brewer's grain (DM=90%)	0%	0%	6%	14%
Feed urea	0%	0%	0%	0%
Mineral salts etc.	4%	4%	0%	0%
Total	**100%**	**100%**	**100%**	**100%**

Table 6.5: Default mix of concentrates **Great Britain**. The contents are shown on dry matter basis.

Feed in concentrate	Low protein		High protein	
	Soy-containing	Soy-free	Soy-containing	Soy-free
Barley	8%	10%	12%	10%
Wheat	8%	10%	12%	10%
Broad beans	0%	0%	0%	0%
Maize grain	2%	0%	0%	5%
Soybean meal	5%	0%	6%	0%
Rapeseed meal	6%	15%	25%	25%
Sunflower cake	8%	10%	0%	25%
Beet pulp, dried (DM=89%)	23%	28%	0%	1%
Molasses	2%	1%	0%	0%
Palm oil (fats)	1%	1%	1%	3%
Palm kernel meal	0%	0%	0%	0%
Wheat husk	16%	10%	16%	0%
Brewer's grain (DM=90%)	20%	15%	25%	20%
Feed urea	0%	0%	3%	2%
Mineral salts etc.	0%	1%	0%	0%
Total	**100%**	**100%**	**100%**	**100%**

6.2 Additional types of purchased feed modelled based on existing feed in the model

Additional types of purchased feed have been added to the data entry sheet of the FarmTool v2021, see **Table 6.6**. This means that these types of feed can only be used for farm specific calculations. Production and property data for the new feed types are based on already existing feed types in the model. This is done at the level of dry matter, e.g. 1 kg rye (85% DM) is represented by 87.5%/85% = 1.03 kg maize.

Table 6.6. List of additional types of feedstuff in the FarmTool, which are modelled by using placeholders. The feed code specified in brackets refer to the code in Møller et al. (2005).

Additional type of purchased feed	Dry matter	Placeholder	Dry matter
Rye (feed code 207)	85%	Maize (feed code 204)	87.5%
Peas (feed code 216)	85.2%	Faba beans (feed code 211)	86.4%
Lupin (feed code 218)	87.9%		
Potato pulp (feed code 273)	16%	Wheat (feed code 203)	85%
Potatoes (feed code 395)	24%		
Carrots (feed code 391)	10%		

7 FarmTool module: Energy

This chapter describes the updates of the energy related modelling in the FarmTool.

7.1 Biodiesel (HVO and RME)

In the FarmTool v2016, the only option for fuel used in milk farms is diesel. In the v2021 update, two types of biobased diesel alternatives have been added: HVO (Hydro treated vegetable oil) based on palm oil and RME (rape methyl ester).

The Arla FarmTool already includes LCI data for crude palm oil and rapeseed oil (Dalgaard and Schmidt 2012). Inputs and outputs of the main flows related to the production of RME are obtained from ecoinvent v.3.6: Vegetable oil methyl ester {Europe without Switzerland}| esterification of rape oil | Conseq (ecoinvent 2019). The main in-and outflows related to the production of HVO are obtained as data on "New EC" from Bonomi et al. (2018, p 41). For HVO, no by-product of propane is considered because this is presumed being used for process energy and for on-site production of hydrogen (Bonomi et al. 2018, p 41).

The reference flows of HVO and RME is accounted in energy unit. The calorific values of HVO and RME are obtained from Neste (2016, p 15) and Nielsen et al. (2016) respectively.

Both RME and HVO are modelled using the same consistent LCI models and cut-off as all remaining activities in the Arla FarmTool.

Table 7.1. Life cycle inventory data for the production of HVO and RME.

Flow	Unit	HVO	RME	
Product outputs				
HVO	MJ	44.1		Reference flow (corresponds to 1 kg HVO)
RME	MJ		37.2	Reference flow (corresponds to 1 kg RME)
Glycerine	kg		0.109	By-product, see below
Potassium sulphate	kg		0.0169	By-product, see below
Material inputs				
Crude palm oil	kg	1.19		Dalgaard and Schmidt (2012, section 5.4)
Crude rapeseed oil	kg		1.03	Dalgaard and Schmidt (2012, section 5.2)
Methanol	kg		0.114	ecoinvent 3.3 (2016): Methanol {GLO}| market
Potassium hydroxide	kg		0.0114	ecoinvent 3.3 (2016): Potassium hydroxide {GLO}| market
Sodium hydroxide	kg	0.00132		ecoinvent 3.3 (2016): Sodium hydroxide, without water, in 50% solution state {GLO}| market
Phosphoric acid	kg	0.00088	0.0046	ecoinvent 3.3 (2016): Phosphoric acid, industrial grade, without water, in 85% solution state {GLO}| market
Energy				
Electricity	kWh	0.137	0.0423	Dalgaard and Schmidt (2012, section 2.3)
Natural gas	MJ		0.924	Dalgaard and Schmidt (2012, section 2.5)

The by-product of glycerine from RME production is modelled using substitution for the consequential model switch and by economic allocation for the IDF switch. For the substitution in the consequential model, the feed value glycerine has been used,: 15.2 MJ gross energy and 0.0041 kg crude protein/kg dm (Kerr et al. 2007). When modelling the glycerine using substitution, the substituted feed is feed energy and feed protein described in Schmidt and Dalgaard (2012, section 9.1). When modelling the glycerine using allocation, the price is estimated based on the substituted feed Dalgaard and Schmidt (2012, appendix C.3).

7.2 Electricity

In the FarmTool v2021, it is enabled for taking into account when a specific farmer uses and produces renewable electricity. The implementation of this is described in this section.

Electricity is divided into:

- Purchased electricity
  - Marginal grid mix, which is used in the consequential model (See Dalgaard and Schmidt 2012, section 2.3)
  - Certified renewable electricity (represented as a mix of 50% wind and 50% biomass)
  - Residual mix, which is defined as the historical average mix minus the certified renewable mix (see **Table 7.2**)
- Production of renewable electricity on the farm
  - Wind and solar (represented by wind)
  - Biogas, farm plant (see section 4.3)
- Production of renewable electricity off-farm
  - Biogas, centralized plant (see section 4.3)

The use of the different mixes of electricity listed above depends on the model switch: consequential or attributional (IDF).

When certified renewable electricity is purchased, it is assumed that this will affect the amount of renewable electricity in the grid correspondingly. In that respect, it has been assumed that the type of purchased certificate assures this. It is noted that the documentation of the effect of certificates is generally poor. It has been out of scope of the current project to assess the additionality of different certification schemes. The actual choice of which certificates to "allow" in the tool is up to Arla Foods. However, it is recommended to initiate an evaluation of certification schemes, since there are probably both certificates on the market with and without effects on the amount of renewable electricity in the grid. Probably power purchase agreements (PPA) are more likely to have an effect.

When a farmer buys a certificate, it is not always known what type of renewable energy that will be installed as a consequence of the purchase of the certificate. Therefore, we have a simplified assumption that this can be modelled as 50% windpower and 50% power based on woodchips. Hence, when a renewable energy certificate at 1 kWh is purchased, the effect is modelled by increasing the inputs of Windpower and power from woodchips by 0.5 kWh and 0.5 kWh respectively, and by reducing the input of electricity from the generic national electricity market by 1 kWh.

Windpower is modelled using data from ecoinvent (2014), and is calculated as the average of 1-3 MW onshore, 1-3 MW off-shore and >3 MW onshore for Denmark.

Electricity from biofuel is modelled using the LCI data for the combustion of biomass described in 'Appendix 1: Modelling of heat' and an assumed fuel to electricity efficiency at 40%.

Consequential model

The consequential model includes the potential offset from production of renewable energy. Hence, the export of electricity from biogas, wind and solar substitutes the marginal.

The consequential model does not operate with the “residual mix”. This because if the certificates affect the amount of renewable electricity in the grid, then it would be misleading to use the residual mix, because the purchased certificates would not be additional to a historical residual.

Equation 7.1

Use of marginal grid mix = purchased + use_of_own_production – production – purchased_certified

Where

Production = produced_wind + produced_solar + produced_biogas_farm + produced_biogas_central

Equation 7.2

Use of wind = (produced_wind + produced_solar) + purchased_certified · share_wind

Use of biomass = purchased_certified · share_biomass

Where

share_wind = share_biomass = 50% is the assumed mix of certified renewable electricity.

Attributional model (IDF)

The attributional model (IDF) does not include effects from exported electricity from biogas, solar or wind power[1]. The total use of electricity is defined as the purchased electricity (divided on certified renewable and residual). The use of certified electricity can both be own or external certificates.

Equation 7.3

Use of wind = purchased_certified · share_wind

Use of biomass = purchased_certified · share_biomass

Equation 7.4

Use of residual = purchased – purchased_certified

The residual mix is presented **Table 7.2**.

[1] It should be noted that this is indeed a deviation from IDF (2015), but Arla wants that the energy part follows the GHG Protocol, where the impacts of energy are allocated to the user of the energy. Hence no credits, when a farmer generates energy as a by-product.

Table 7.2. Residual electricity mix used in IDF switch (Thinkstep 2019).

Source of electricity	DE	DK	GB	SE	Comments
Photovoltaic	0.0%	4.0%	1.4%	1.3%	
Windpower	0.5%	4.7%	1.7%	5.0%	
Hydropower	1.1%	3.1%	1.5%	15.7%	
Geothermal	0.1%	0.0%	0.0%	0.0%	
Biomass	0.0%	2.3%	0.0%	10.0%	
Nuclear	18.2%	19.0%	27.3%	62.7%	
Lignite	34.6%	11.9%	0.0%	0.0%	
Hard coal	21.2%	28.2%	9.3%	0.8%	
Natural gas	20.9%	22.3%	57.8%	0.0%	
Oil	1.1%	0.9%	0.0%	0.3%	
Renewable unspecified	0.1%	0.1%	0.0%	0.5%	Modelled as wind
Fossil unspecified	2%	4%	1%	4%	Modelled as hard coal
Total	**100%**	**100%**	**100%**	**100%**	

8 Uncertainties

The model and data uncertainties for national milk baselines are evaluated in Schmidt and Dalgaard (2012). Since the current study uses the same model (with updates) and the same type of data, a new sensitivity analysis is not carried out. The below assessment is based on Schmidt and Dalgaard (2012).

Model uncertainties: The model is fully parameterised, so it can be seen as an empty shell that only makes sense when it is filled with input parameters (national average data or farm specific data). The model framework is highly flexible and can handle most changes in assumptions regarding modelling of co-product allocation, market mixes, completeness and land use changes. The model uncertainties are mainly related to the applied emission models. Most of these are adopted from IPCC (2006), though some are based on more accurate modelling, e.g. energy requirement for cows. Emission factors and models from IPCC are characterised by being applicable to all countries and crop/animal types, which makes the choice of emission models very consistent and comparable across crops and animals in different parts of the world. This is an important feature since the milk system potentially affects production processes in many parts of the world. On the other hand, the IPCC models are sometimes not fully adjusted to local conditions and they have not enough level of detail for capturing all relevant aspects. In general, the applied emission models are regarded as being related to some uncertainties, but at the same time they also allow for comparison across geographical locations and different crops and animals.

Data uncertainties: For the national baselines, the most important assumptions relate to the animal turnover, the feed composition, the identification of substituted beef system (only ISO 14040/44 switch) and indirect land use changes model. The collected data on animal turnover and feed composition are regarded as being related to a low degree of uncertainty. The identification of Brazilian beef as the substituted beef system is associated with significant uncertainties. The effect of this has been tested in Schmidt and Dalgaard (2012, chapter 11.1), where it appears that the results are sensitive to the identification of the beef system. The uncertainties related to land use changes are also significant; In Schmidt et al. (2015) the major sources of uncertainty are related to the proportion between yield increases and land transformation, and to the modelling of yield increases which are modelled assuming only additional fertiliser as a flexible mean of increasing yields.

It should be noted that the data used for the background system to account for the production of fertilisers, electricity, fuels, chemicals, transport, machinery and buildings are based on ecoinvent v2 and 3, i.e they are becoming outdated. The background system will be updated in 2022. It should be noted that the background system based on ecoinvent v2 and 3 account for a relatively small part of the overall GHG emissions; <10%.

The uncertainties related to the applied switch modes available in the study are mainly related to the methodological problems with the switches for the IDF Guideline (IDF 2015). This include:

- Lack of cause-effect relationships, e.g. when constrained suppliers are included in the inventoried system, see Weidema et al. (2020), Schmidt (2010) and Weidema et al (2009)
- Allocated processes do not fulfil the mass balance principle (when inputs are allocated in another unit than their mass, the mass balance will be lost), see Weidema and Schmidt (2010).
- Land use changes are either excluded or included according to the same approach as in PAS2050, which uses a historical approach to land use changes for the land on which crops are grown. Hereby, there is a lack of cause-effect relationship between the use of land and land use changes.

- The exclusion of capital goods and/or services leads to incomplete results, and potentially comparisons may be misleading if the compared systems are related to different emissions from these input categories.

9 Sensitivity, completeness and consistency checks

According to ISO 14044 (2006) an evaluation in the interpretation phase including sensitivity, completeness and consistency check must be carried out in order to establish confidence in the results of the LCA. The sensitivity, completeness and consistency checks presented in the following are similar to Schmidt and Dalgaard (2012). This is because the current study uses the same model (with updates) and the same type of data as Schmidt and Dalgaard (2012).

9.1 Sensitivity check

The objective of the sensitivity check is to assess the reliability of the results and how they are affected by system boundaries, uncertainties in data, assumptions and LCIA-methods (ISO 14044 2006).

In **chapter 8**, the major source of uncertainty relating to the model is identified as the inherent uncertainties related to the applied emission models from IPCC. The choice of these models relies on a compromise to be able to consistently us the same models throughout the study for all regions and crops/animals whereas more country specific models may be related to smaller levels of uncertainty.

Uncertainty in data: In **chapter 8**, the most critical uncertainties in data are identified as the ones relating to the animal turnover (incl. animals weights), feed composition, identification of the substituted beef system and the data used for the modelling of indirect land use changes.

LCIA-method: The IPCC GWP100 method (IPCC 2013) is used with adjustments according to Muñoz and Schmidt (2016), where biogenic and fossil CH_4 have characterisation factors at 27.75 and 30.5 respectively. The IPCC GWP-method weight the relative importance of different GHG-emissions (CO_2, N_2O, CH_4 etc.) based on a different emissions cumulative radiation forcing within a time horizon of 100 years. Some effects related to global warming have impacts which relevant in a shorter short time frame than 100 years (e.g. biodiversity caused by changing ecozones and extreme weather) while other impacts are more relevant for the longer term (e.g. increases in sea level). Therefore, ideally GHG-emissions should be assessed using different indicators representing different impacts. However, such indicators are not immediately available and widely accepted. Therefore, the current study only uses GWP100, which currently is the most accepted and widely used indicator for GHG-emissions.

9.2 Completeness check

The objective of a completeness check is to ensure that the information provided in the difference phases of the LCA are sufficient in order to interpret the results (ISO 14044 2006).

The life cycle inventory consistently operates with a cut-off criterion at 0% for the consequential model (ISO 14040/44) and by excluding services for the IDF switch.

9.3 Consistency check

The objective of the consistency check is to verify that assumptions, methods and data are consistent with the goal and scope. Especially the consistency regarding data quality along the product chain, regional/temporal differences, allocation rules/system boundaries and LCIA are important (ISO 14044).

In general, the model is based on a very consistent and well-defined methodological framework as presented in Schmidt and Dalgaard (2012). This framework and data enables for consistently and system wide applying different modelling assumptions and levels of completeness in the inventory.

The applied emissions models for direct emissions in agriculture from animals and crop cultivation are all based on IPCC (2006).

In general, the study is regarded as having a very high degree of consistency.

10 Conclusion

This report presents updates of the Arla FarmTool compared to the previous 2016 version (Dalgaard et al. 2016). The updates includes the addition of a comprehensive range of best techniques for mitigating GHG emissions in the milk life cycle production system. The new modules of best techniques include various alternative techniques for:

- Manure acidification
- Anaerobic digestion of manure
- Renewable energy

Besides adding new technologies, the update also includes a significant increase in the granularity of data input types to be included in the calculations. This includes:

- New crop types
- Option to specify the time for incorporation of solid manure/deep litter after land application
- Option to specify feed properties of concentrates:
    - content of proteins
    - content of fatty acids
    - indicate if the concentrate is soy-free

Further, the update includes a number of changes of the methodology. The most significant change is the way the beef by-product (live animals) is estimated. Before, this was based on specification of the number of animals sent to slaughterhouse and their weights. Due to lack of data on this at the farm level as well as uncertainties caused by temporal variations, it has been decided to change the approach so that the by-product of live animals to slaughterhouse is nor calculated based on generic data on weight gain.

11 References

Bentivoglio D, Finco A, Bacchi M R P, Spedicato G (2014). European biodiesel market and rapeseed oil: what impact on agricultural food prices? International Journal of Global Energy Issues, 2014 Vol.37 No.5/6, pp 220-235.

Birkmose T (2014). Effekten af nedfældning –dokumentation for effekten af ammoniakfordampning og lugtgener. AgroTech, Denmark. Available online at: https://mst.dk/media/mst/9069956/nedf_ldning_ammoniakfordampning_lugt_endelig_version.pdf Accessed 30/1/2019. (In Danish)

Blonk Agri-footprint BV (2017). Agri-Footprint – Part 2 – Description of data. Gouda, the Netherlands.

Dalgaard R and Schmidt J (2012a). National and farm level carbon footprint of milk - Life cycle inventory for Danish and Swedish milk 2005 at farm gate. Arla Foods, Aarhus, Denmark.

Dalgaard R and Schmidt J (2012b). National carbon footprint of milk - Life cycle assessment of Danish and Swedish milk 1990 at farm gate. Arla Foods, Aarhus, Denmark

Dalgaard R, Schmidt J, Flysjö A (2014). Generic model for calculating carbon footprint of milk using four different LCA modelling approaches. Journal of Cleaner Production 73:146-153.

Dalgaard R, Schmidt J and Cenian K (2016). Life cycle assessment of milk - National baselines for Germany, Denmark, Sweden and United Kingdom 1990 and 2012. Arla Foods, Aarhus, Denmark.

Danish Environmental Protection Agency (2019). List of Environmental Technologies. Available online at: https://eng.mst.dk/trade/agriculture/environmental-technologies-for-livestock-holdings/list-of-environmental-technologies/ Accessed January 2019.

De Rosa M, Dalgaard R, Schmidt J (2013). National carbon footprint of milk - Life cycle assessment of British and German milk 1990 at farm gate. Arla Foods, Aarhus, Denmark http://lca-net.com/p/2329

De Rosa M, Schmidt J, Brandão M, Pizzol M (2017). A flexible parametric model for a balanced account of forest carbon fluxes in LCA. International Journal of Life Cycle Assessment 22:172–184.

ecoinvent (2014). ecoinvent data v3.1. Swiss Centre for Life Cycle Inventories, St. Gallen.

ecoinvent (2019). ecoinvent data v3.6. Swiss Centre for Life Cycle Inventories, St. Gallen.

European Commission (2007). Reference Document on Best Available Techniques for the Manufacture of Large Volume Inorganic Chemicals - Ammonia, Acids and Fertilisers, Integrated Pollution Prevention and Control, European Commission.

Hansen MN, Sommer SG, Hutchings NJ, Sørensen P (2008). Emission factors for calculation of ammonia volatilization by storage and application of animal manure. DJF Husdyrbrug nr. 84. Aarhus Universitet. Det Jordbrugsvidenskabelige Fakultet. (In Danish)

IDF (2010). A Common Guide for Carbon Footprint Approach for Dairy - The IDF guide to standard life cycle assessment methodology for the dairy sector. Bulletin of the International Dairy Federation 445/2010. Brussels.

IDF (2015). A Carbon Footprint Approach for the Dairy Sector - The IDF guide to standard life cycle assessment methodology. Bulletin of the International Dairy Federation 479/2015. Brussels. https://store.fil-idf.org/publications/?free_file_download=3827 Accessed October 2018.

IEA (2018). IEA headline global energy data. International Energy Agency. http://www.iea.org/media/statistics/IEA_HeadlineEnergyData.xlsx Accessed March 2019

IPCC (2006). 2006 IPCC Guidelines for national greenhouse gas inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H S, Buendia L, Miwa K, Ngara T and Tanabe K (eds). IGES, Japan http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html (Accessed November 2019)

IPCC (2013). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York.

IPCC (2006), 2006 IPCC Guidelines for national greenhouse gas inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H S, Buendia L, Miwa K, Ngara T and Tanabe K (eds). IGES, Japan. Available online at: https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html Accessed 24/1/2019.

Kai P (2019), Senior Advisor. Department of Engineering, Aarhus University. Personal communication by e-mail 23/1/2019.

Kai P, Tybirk P, Jensen M L, Elvstrøm J Bækgaard H (2014). Kap. 8. Tab fra stalde. Available online at: http://anis.au.dk/fileadmin/DJF/Anis/dokumenter_anis/Normtal_for_husdyrgoedning_Kapitel_8_Stalde_2014.pdf Accessed 24/1/2019. (In Danish)

Kerr B J, Dozier W A, Bregendahl K (2007). Nutritional value of crude glycerin for nonruminants. Proc 23rd Annual Carolina Swine Nutrition Conference, November 13, Raleigh, NC, USA. pp: 6-18. Accessed April 2020: https://www.biofuelscoproducts.umn.edu/sites/biodieselfeeds.cfans.umn.edu/files/2007-kerr-nutritional_value_of_crude_glycerin_for_non-ruminants.pdf

Landbrugsstyrelsen (2018). Vejledning om gødsknings- og harmoniregler. Planperioden 1. august 2018 til 1. juli 2019. Miljø- og Fødevareministeriet. (In Danish).

Mergner R, Rutz D, Wagner I, Amann S, Amann C, Kulisic B, Abramovic J, Vorisek T, Allegue L B, Hinge J, De Filippi F, Dzene I, Surowiec M, Adamescu C, Ofiteru A (2013). European Strategy Paper on Heat Use from Biogas Plants. Accessed March 2019: http://www.biogasheat.org/wp-content/uploads/2013/12/BiogasHeat-Strategy-paper_FINAL.pdf

Mikkelsen MH, Albrektsen R, Gyldenkærne S (2011). Danish emissions inventory for agriculture. Inventories 1985 – 2009. NERI Technical Report no. 8. National Environmental Research Institute. Aarhus University, Denmark.

Mikkelsen MH, Albrektsen R, Gyldenkærne S (2016). Biogasproduktions konsekvenser for drivhusgasudledning i landbruget. Aarhus Universitet, DCE – Nationalt Center for Miljø og Energi, 41 s. - Videnskabelig rapport fra DCE - Nationalt Center for Miljø og Energi nr. 197. Available online at: http://dce2.au.dk/pub/SR197.pdf Accessed 25/1/2019. (In Danish)

Miljøstyrelsen (2010a). Nedfældning af gylle i græsmarker. 1. edition. Available online at: https://mst.dk/media/mst/66960/Nedf%C3%A6ldning%20gr%C3%A6smarker_klargjort_101112.pdf Accessed 24/1/2019. (In Danish)

Miljøstyrelsen (2010b). Nedfældning af gylle i sort jord. Available online at: https://www2.mst.dk/Wiki/GetFile.aspx?File=/BAT/Teknologiblade/Udkast_nedfaeldning_sortjordredigeretaflonkh.pdf Accessed 24/1/2019. (In Danish)

Miljøstyrelsen (2010c). Teknologiblad. Opbevaring af husdyrgødning -fast overdækning af gyllebeholder. Available online: https://www2.mst.dk/wiki/GetFile.aspx?File=/BAT/Teknologiblade/Fastoverdaekning_svin_mink_kvaeg_endelig_101108.pdf Accessed 17/1/2019. (In Danish)

Miljøstyrelsen (2011). Svovlsyrebehandling af gylle. Available online at: https://www2.mst.dk/wiki/GetFile.aspx?File=/BAT/Teknologiblade/Malkekvaeg_Svovlsyrebehandlingafgylle_version4.pdf Accessed 12/11/2018. (In Danish)

Mogensen L, Knudsen T M, Dorca-preda T, Nielsen N I, Kristensen I S, Kristensen T (2018). Bæredygtighedsparametre for konventionelle fodermidler til kvæg - metode og tabelværdier [English: Sustainability parameters for conventional feed for cattle]. DCA Rapport nr. 116. Aarhus University. Accessed December 2019: https://dcapub.au.dk/djfpublikation/djfpdf/DCArapport116.pdf

Nasir IM, Mohd Ghazi TI, Omar R (2012). Anaerobic digestion technology in livestock manure treatment for biogas production: A review. Eng Life Sci 12:258–269

Neste (2016). Neste Renewable Diesel Handbook. Neste. Accessed 20200423: https://www.neste.com/sites/default/files/attachments/neste_renewable_diesel__handbook.pdf

Nielsen OK, Plejdrup MS, Winther M, Nielsen M, Gyldenkærne S, Mikkelsen MH, Albrektsen R, Thomsen M, Hjelgaard K, Fauser P, Bruun HG, Johannsen VK, Nord-Larsen T, Vesterdal L, Callesen I, Schou E, Suadicani K, Rasmussen E, Petersen SB, Baunbæk L, Hansen MG (2016). Denmark's National Inventory Report 2015 and 2016. Emission Inventories 1990-2014 - Submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol. Aarhus University, DCE – Danish Centre for Environment and Energy, 943pp. Scientific Report from DCE – Danish Centre for Environment and Energy.

Nielsen et al. (2018). Denmark's National Inventory Report 2018, Emission Inventories 1990-2016 - Submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol.

Nielsen I N (2020). Personal communication with Nicolai Ingemann Nielsen, Chefkonsulent, cand.agro., ph.d., HusdyrInnovation, Landbrug & Fødevarer F.m.b.A., SEGES.

Odderskær P, Topping C, Petersen MB, Rasmussen R, Dalgaard T, Erlandsen M (2006). Ukrudtstriglingens effekter på dyr, planter og ressourceforbrug. Bekæmpelsesmiddelforskning fra Miljøstyrelsen nr. 105. Avaiable online at: https://www2.mst.dk/udgiv/publikationer/2006/87-7052-343-6/pdf/87-7052-344-4.pdf Accessed 22/1/2019. (In Danish)

Olesen JE, Petersen SO, Lund P, Jørgensen U, Kristensen T, Elsgaard L, Sørensen P, Lassen J (2018). Virkemidler til reduktion af klimasser i landbruget. DCA report nr. 130. Aarhus University, DCA - Danish Centre For Food And Agriculture. Available online at: http://web.agrsci.dk/djfpublikation/index.asp?action=show&id=1273 Accessed 14/11/2018. (In Danish).

Plantedirektoratet (2011). Vejledning om gødsknings- og harmoniregler. Ministeriet for Fødevarer, Landbrug og Fiskeri.

Poulsen H D, Børsting C F, Rom H B , Sommer S G (2001). Kvælstof, fosfor og kalium i husdyrgødning – normtal 2000. DJF rapport Husdyrbrug 36. 154 pp. (In Danish).

Ramanauskaite R, Rutz D, Amann S, Amann C, Abramovic J, Vorisek T, Allegue LB, Hinge J, Dzene I, De Filippi F, Surowiec M, Adamescu C, Ofiteru A (2012). Biogas markets and the use of heat of biogas plants in Austria, Croatia, Czech Republic, Denmark, Germany, Italy, Latvia, Poland and Romania.

Schmidt J (2010). Challenges relating to data and system delimitation in Life Cycle Assessments of food products. Pp. 83-97 in Sonnesen U, Berlin J and Ziegler F (eds.): Environmental assessment and management in the food industry: Life cycle assessment and related approaches. Woodhead Publishing Series in Food Science, Technology and Nutrition No. 194. ISBN 978-1-84569-552-1.

Schmidt J and Dalgaard R (2012). National and farm level carbon footprint of milk - Methodology and results for Danish and Swedish milk 2005 at farm gate. Arla Foods, Aarhus, Denmark. Available online at: https://lca-net.com/files/Arla-Methodology_report_20120724.pdf

Schmidt J, Brandão M (2013). LCA screening of biofuels – iLUC, biomass manipulation and soil carbon. This report is an appendix to a report published by the Danish green think tank CONCITO on the climate effects from biofuels: Klimapåvirkningen fra biomasse og andre energikilder, Hovedrapport (in Danish only). CONCITO, Copenhagen. http://lca-net.com/p/227 Accessed October 2018.

Seidel A, Pacholskia A, Nyord T, Vestergaard A, Pahlmanna I, Herrmann A, Kage H (2017). Effects of acidification and injection of pasture applied cattle slurry on ammonia losses, N_2O emissions and crop N uptake.

Styles D, Dominguez EM, Chadwick D (2016). Environmental balance of the of the UK biogas sector: An evaluation by consequential life cycle assessment. Sci Total Environ 560–561:241–253.

Sørensen O, Khan AR, Møller HB, Thomsen IK (2012). Effect of anaerobic digestion of organic manures on N turnover and N utilization. Nitrogen Workshop 2012. Available online at: http://orgprints.org/21820/1/21820.pdf Accessed 31/01/2019.

Sørensen P, Børgesen CD (2015). Kvælstofudvaskning og gødningsvirkning ved anvendelse af afgasset biomasse. DCA report nr. 065. Aarhus University, DCA - Danish Centre For Food And Agriculture. Available online at: https://pure.au.dk/portal/files/93094219/DCArapport065.pdf Accessed 21/11/2018. (In Danish)

Thinkstep (2019). Process data set: Residual grid mix; AC, technology mix; consumption mix, to consumer. Thinkstep. Accessed June 2020: http://gabi-documentation-2019.gabi-software.com/xml-data/processes/470b8025-0616-4847-a111-a9ab50712fcc.xml

Toft M (2019). Biocover. www.biocover.dk. Vejen Denmark. Personal communication by e-mail and phone 29/1/2019.

Thrän D, Schaubach K, Benedetti L, Bruce L, Coelho S, Craggs L, Diaz-Chavez R, Escobar F, Goldemberg J, Guisson R, Hansen MT (2017). Global wood pellet industry market and trade study, IEA Bioenergy Task 40.

UNFCCC (2019). National Inventory submissions 2018. https://unfccc.int/process/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/national-inventory-submissions-2018 Accessed 8/3-2019.

VERA (2012). Vera Verification Statement. Verification of environmental technologies for agricultural production. Available online at: http://www.vera-verification.eu/fileadmin/download/VERA_Statements/VERA-Statement001_SyreN.pdf Accessed 24/1/2019.

Volden H (2011). NorFor – The Nordic feed evaluation system. EAAP publication No. 130. EAAP – European Federation of Animal Science & NorFor Nordic feed evaluation system. Wageningen. The Netherlands.

Weidema B P, Ekvall T, Heijungs R (2009). Guidelines for applications of deepened and broadened LCA. Deliverable D18 of work package 5 of the CALCAS project. https://lca-net.com/p/186

Weidema B P, Schmidt J (2010). Avoiding allocation in life cycle assessment revisited. Column for Journal of Industrial Ecology 14(2):192-195.

Weidema B P, Simas M S, Schmidt J, Pizzol M, Løkke S, Brancoli P L (2020). Relevance of attributional and consequential information for environmental product labelling. The International Journal of Life Cycle Assessment 25:900–904.

Appendix 1: Modelling of heat

Heat is an important by-product from the utilisation of biogas from anaerobic digestion. The new version of the FarmTool has updated the processes associated with heat production.

Heat use in the agricultural sector

There is a variety of fuels that can be used for heating in the agricultural sector. Data on the energy consumption in the agricultural sector per country are obtained from IEA (2018). IEA (2018) provide data on the total energy use by the sector, including fuels for traction and heat, district heating as well as electricity. It has been assumed that electricity and oil products are fully used for other purposes than heating. The reasoning behind is that most of the farm use of electricity and oil products will be in processing and field operations, not heat. IEA (2018) statistics does not contain information on heat used by the agriculture sector in Germany. Instead, data on the residential sector is used as an approximation for Germany.

Following the two different modelling options in the FarmTool, namely IDF and consequential modelling, the heat is modelled in two different ways:

- Average & substitution reflecting the modelling assumptions in IDF (2015)
- Marginal & substitution reflecting the modelling assumptions in ISO 14044 and Weidema et al. (2009)

The average approach is applying the average mix of heat sources in 2012, while the marginal approach is applying a mix calculated based on the change in the most recent five-year span, i.e. between 2011 and 2016. For the latter, only sources that have expanded are included, i.e. only the sources of heat that have increased they production volume. This approach is in accordance with the approach for the modelling of marginal electricity described in Schmidt et al. (2011).

Table 0.1. Heat sources for the use of heat in the agricultural sector in DE, DK, SE and UK.

Heat source	**DE**		**DK**		**SE**		**UK**	
Modelling approach	**Average**	**Marginal**	**Average**	**Marginal**	**Average**	**Marginal**	**Average**	**Marginal**
District heating	8%	12%	22%	26%	3%	8%		
Biomass	14%	21%	32%	65%	87%	92%	12%	49%
Natural gas	48%	57%	29%	9%	10%		87%	51%
Heating oil	29%	10%						
Coal			17%				0%	
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

The production of district heating is described in the section below.

It appears from **Table 0.2** to **Table 0.4** that farms rely considerably on biomass as a source of heat. Biomass use requires special attention, due to potential indirect land use change (iLUC) and the effect of accelerated CO_2 emissions Schmidt and Brandao (2013). This is further described in the following section: '**Biomass production and combustion**' on page 55.

The combustion emissions as well as the life cycle emissions related to the production of the other fuels **Table 0.2** are described in Dalgaard and Schmidt (2012, section 2.5).

District heating

District heating is generally sourced by either combined heat and power plants (producing both heat and electricity) or by heat plants (producing only heat). Following the same approach as for heat use in the agricultural sector (**Table 0.1**), the average and marginal sources of district heating are identified based on the information in EIA (2018). The result of this is presented in **Table 0.2**. The fuel inputs to the CHP and heat plants are presented in **Table 0.3** and **Table 0.4** respectively.

Table 0.2. Sources of district heating divided on CHP and heat plants in DE, DK, SE and UK.

Source of district heating	DE		DK		SE		UK	
Modelling approach	Average	Marginal	Average	Marginal	Average	Marginal	Average	Marginal
CHP	72%	100%	73%		74%	100%		
Heat plants	28%		27%	100%	26%		100%	100%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Below in **Table 0.3** and **Table 0.4**, the inputs and outputs of the affected CHP and heat plants in **Table 0.2** (i.e. the ones with >0%) are presented.

Table 0.3. Fuel inputs and electricity outputs of **CHP plants** in DE, DK, SE and UK. The data are scaled to an input of 1 MJ fuels, thus the heat and electricity efficiencies can be directly read in the "Heat" and "Electricity" rows. Unit: MJ.

Inputs and outputs of CHP plants	DE		DK		SE		UK	
Modelling approach	Average	Marginal	Average	Marginal	Average	Marginal	Average	Marginal
Output: Reference product								
Heat	0.6	0.6	0.6		0.6	0.6	0.6	
Output: By-product								
Electricity	0.3	0.3	0.3		0.3	0.3	0.3	
Fuel inputs								
Biomass	0.28	0.58	0.34		0.81	1	0.16	
Natural gas	0.43	0.37	0.19		0.06		0.72	
Coal	0.27	0.05	0.45		0.1		0.05	

Table 0.4. Fuel inputs and electricity outputs of **heat plants** in DE, DK, SE and UK. The data are scaled to an input of 1 MJ fuels, thus the heat efficiency can be directly read in the "Heat" row. Unit: MJ.

Inputs and outputs of heat plants	DE		DK		SE		UK	
Modelling approach	Average	Marginal	Average	Marginal	Average	Marginal	Average	Marginal
Output: Reference product								
Heat	0.68		1	1	0.86		0.61	0.61
Fuel inputs								
Biomass	0.34		0.61	0.58	0.9		0.04	
Natural gas	0.45		0.34	0.42	0.02		0.78	1
Coal	0.17		0		0.03		0.15	

Biomass production and combustion

The use of wood as a fuel has been rising in Europe in recent years (Camia et al. 2018). The rise of wood for energy purposes, particularly wood pellets, has been met by increasing imports (Camia et al. 2018). EU demand has outpaced production in the last ten years and a significant share of the rising imports come from US (Flach et al. 2017). The expansion of wood pellet production in US has taken place almost exclusively in the Southeast, due to the proximity to European markets and other strategic reasons (Thrän et al. 2017). Therefore, changes in demand for heat from biomass are expected to affect the US production of pellets.

Wood pellets can be produced from mill residues or dedicated plantations. The rise on production in wood pellets in south US has been met by increasing use of softwood pulpwood, while the amount of feedstock coming from mill residues has been constant (figure 4.11, IEA, 2017). This suggests mill-residues are already fully utilised and any change in the demand will affect pulpwood plantations. The inventory is based on the production of loblolly pine, since it is the most widely grown species for pulpwood in the region.

The energy and machinery use for forestry operations relating to the extraction of wood for biomass production are obtained from the following ecoinvent v3.1 activity (ecoinvent 2014):

- Pulpwood, softwood, measured as solid wood under bark {RoW}| softwood forestry, pine, sustainable forest management

The consequential and attributional (allocation at point of substitution) models are used for the ISO 14044 and IDF switches in the Arla model respectively.

The carbon balance and time dependant CO_2 fluxes are calculated using the model described in De Rosa et al. (2017).

Table 0.5. Input data for the forest balance model for loblolly pine in SE US.

Parameter	Unit	Wood, loblolly pine (dm) {US}	Reference
Rotation time	year	12	Schmidt and Brandao (2013)
Biomass annual increment (BAI)	m^3 ha^{-1} $year^{-1}$	14	Schmidt and Brandao (2013)
Basic Wood Density (conversion factor m^3-> t)	t dm $m^{3\ -1}$	0.42	Schmidt and Brandao (2013)
Carbon factor (C content in wood)	t C t dm^{-1}	0.51	IPCC (2006, table 4.3)
R (Belowground/aboveground)	factor	0.29	IPCC (2006, table 4.4)
BCEFS (biomass conversion and expansion factor: merchantable growing stock volume to above-ground biomass)	t dm $m^{3\ -1}$	0.75	IPCC (2005, table 4.5)
Share of above ground slashes and woody debris harvested	share	80%	Assumption
Share of below ground woody debris harvested	share	0%	Assumption

Table 0.6. LCI data for the burning of wood chips and for the cultivation of loblolly pine in SE US.

Inputs and outputs	Unit	Wood chips incl. burning as dm	Wood, loblolly pine (dm) {US}
Reference flow			
Wood chips incl. burning as dm	ton	1	
Wood, loblolly pine (dm) {US}	ton		1
Inputs from ecoinvent process			
Diesel	MJ		2.8
Other inputs (per m^3 wood)	m^3		2.1
Land tenure, intensive forest (iLUC)	ha year eq.		0.094
Emissions			
CO_2 biogenic	ton		0.77
CO_2-eq	ton		0.71
Resource inputs			
CO_2 in air	ton	1.87	2.65
CO_2-eq	ton	1.87	2.53
Occupation, forest	ha year		0.11

The mass of biomass is converted to energy units by assuming that the calorific value is 17.5 MJ/kg (Nielsen et al. 2018).

Appendix 2: Feed properties

Feed properties are based on Møller et al. (2005). In the table below, the "code" refers to the corresponding feed code in Møller et al. (2005). The last two columns are calculated feed properties:

- Gross energy (GE) [MJ] = 24.1 [MJ/kg] · raw protein [kg] + 36.6 [MJ/kg] · fat [kg] + 18.5 [MJ/kg] · carbohydrate [kg]
- DIgestible energy = digestible energy [MJ/kg dm] divided by Gross energy [MJ/kg dm]

			Input data						Calculated data	
			Dry matter content	Raw protein	Raw fat	Carbo-hydrate	Digestable energy	Feed energy content (net energy)	Gross energy	Digestible energy as share of gross energy
Feed	no	Code	kg DM/kg	kg/kg DM	kg/kg DM	kg/kg DM	MJ/kg DM	MJ/kg DM	MJ/kg DM	MJ/MJ
Barley	1	201	0.850	0.108	0.031	0.838	15.2	8.25	19.2	0.790
Wheat	2	203	0.850	0.115	0.024	0.842	16.0	8.99	19.2	0.832
Triticale	3	209	0.850	0.105	0.025	0.848	15.8	8.84	19.1	0.826
Oat	4	202	0.850	0.102	0.053	0.819	13.4	6.76	19.5	0.685
Corn	5	204	0.875	0.096	0.046	0.843	16.2	9.06	19.6	0.827
Broad beans	6	211	0.864	0.311	0.015	0.636	15.9	8.69	19.8	0.803
Soybean meal	7	154	0.874	0.535	0.028	0.361	18.0	10.40	20.6	0.874
Soybean cake	8	151	0.880	0.495	0.137	0.575	16.8	9.29	27.6	0.609
Rapeseed meal	9	142	0.882	0.388	0.042	0.486	15.2	8.02	19.9	0.765
Rapeseed cake	10	144	0.889	0.350	0.105	0.475	16.2	8.84	21.1	0.769
Rapeseed (wholeseed)	11	213	0.925	0.194	0.502	0.262	23.1	13.97	27.9	0.828
Sunflower meal	12	165	0.890	0.417	0.030	0.467	15.1	7.95	19.8	0.763
Beet pulp, dried	13	283	0.894	0.096	0.012	0.822	14.6	7.43	18.0	0.813
Beet pulp, pressed, ensiled, 5% molasses	14	284	0.241	0.104	0.014	0.810	14.8	7.65	18.0	0.822
Molasses, beet	15	277	0.740	0.130	0.001	0.742	13.6	7.28	16.9	0.805
Palm oil	16	347	0.990	0.000	1.000	0.000	32.2	20.95	36.6	0.880
Palm kernel meal	17	136	0.906	0.170	0.082	0.707	12.8	6.17	20.2	0.634
Wheat bran	18	232	0.871	0.183	0.046	0.713	13.1	6.61	19.3	0.679
Feed urea	19	760	1.000	2.280	0	0	0.0	0.00	0.0	0.000
Minerals, salt etc.	20	n.a.	1.000	0	0	0	0.0	0.00	0.0	0.000
Straw	21	781	0.850	0.040	0.019	0.896	7.6	1.71	18.2	0.417
Cover crop used as feed	22	as 24	0.360	0.162	0.044	0.691	13.0	6.14	18.3	0.710
Grass, extensive pasture	23	458	0.180	0.200	0.039	0.661	13.2	6.39	18.5	0.714
Grass, Intensive, permanent pasture (>4 years)	24	565[2]	0.360	0.162	0.044	0.691	13.0	6.14	18.3	0.710
Grass, Rotational grass (< 5 years)	25	525[2]	0.360	0.173	0.044	0.679	13.0	6.14	18.3	0.709

[2] Crude protein and SFU/dm are based on field triels. Data are provided by Arla.

… continued…

Feed	no	Code	Input data						Calculated data	
			Dry matter content	Raw protein	Raw fat	Carbo-hydrate	Digestable energy	Feed energy content (net energy)	Gross energy	Digestible energy as share of gross energy
			kg DM/kg	kg/kg DM	kg/kg DM	kg/kg DM	MJ/kg DM	MJ/kg DM	MJ/kg DM	MJ/MJ
Grain whole crop	26	583	0.340	0.101	0.020	0.824	11.9	5.42	18.4	0.646
Legume whole crop silage	27	600	0.320	0.154	0.020	0.750	12.5	5.87	18.3	0.682
Maize ensilage	28	593	0.330	0.079	0.022	0.863	13.3	6.54	18.7	0.712
Malt sprouts	29	265	0.950	0.289	0.028	0.619	13.6	6.91	19.4	0.700
Brewer's grain (fresh)	30	266	0.245	0.238	0.100	0.612	14.1	7.21	20.7	0.681
Distillers grains, barley based, dry	31	262	0.900	0.320	0.070	0.554	14.9	8.02	20.5	0.726
Milk replacer	32	311	0.950	0.280	0.180	0.470	19.3	11.44	22.0	0.876
Fodder beets	33	351	0.180	0.074	0.004	0.842	14.0	7.36	17.5	0.800