Nitrogen and Energy Utilization on Conventional and Organic Dairy Farms in Norway

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Tingvoll, Norwegen, 2. September 2016, sign. Matthias Koesling

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This work has been accepted by the Faculty of Organic Agricultural Sciences of the University of Kassel as a thesis for acquiring the academic degree of
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Preface

The work in this thesis focuses on the utilization of nitrogen and energy on dairy farms in Norway. I submit the thesis to fulfil the requirements for the degree “Doktor der Agrarwissenschaften” (Dr. agr.) to the University of Kassel, Faculty of Organic Agricultural Sciences (FB 11).

The work with this thesis was part of the project “Environmental and economical sustainability of organic dairy farms” (EnviroMilk). I am grateful, for the funding by the Research Council of Norway (grant number 199487/E40) and ‘Møre og Romsdal’ County Council, Division for Agriculture. Thanks to my former director Kristin Sørheim at the Bioforsk Food and Farming division and latterly Dr. Audun Korsæth, head of the Department for Agricultural Technology and System Analysis at NIBIO, for supporting me and my work.

Many thanks to my supervisor Prof. Dr. Gerold Rahmann for the interest in my work, constructive meetings on planning the work and being accessible when needed, wherever he happened to be in the world. He enabled me to be part of the institute for organic farming in Trenthorst and to work with other doctoral students during several stays. Dr. Sissel Hansen (Bioforsk/NORSØK) was the project leader for EnviroMilk and my co-supervisor. She was always available for planning, discussing and sharing her experience and knowledge, guiding me through this thesis. Many people were involved and helped me. I include here only those who contributed directly to the thesis for a longer period, but I am also grateful for all help I got from people not mentioned here.

Dr. Gustav Fystro and Dr. Ola Flaten contributed to planning and carrying out data collection, and together with Maximilian Schüler to interpreting and discussing the data. Many thanks to Dr. Thomas Nemecek and Dunja Dux at Agroscope in Switzerland for sharing their knowledge on calculating embodied energy, and to Ass. Prof. Gesa Ruge, University of Canberra in Australia for helping to calculate the amount of embodied energy in buildings. The EnviroMilk project would not have been possible without the participating farmers and their interest and willingness to cooperate, as well as all other project partners for discussing how to plan and conduct the study and evaluating its results. Staff at the former Bioforsk Organic Food and Farming Division, some of them now working in the Norwegian Institute of Bioeconomy Research (NIBIO) and others in the Norwegian Centre for Organic Agriculture (NORSØK), made valuable contributions. Turid Strøm, Martha Ebbesvik and Rose Bergslid helped to plan data collection, discuss results and gather data on farms. Dr. Unni Støbet Lande helped with different maps, Dr. Alem Kidane worked on ingredients for concentrates, Borghild Hongset Gjørsvik entered data and Bo Willem Woelfert helped with calculations, layout and figures. I am grateful to Dr. Andrew Pope (chapter 3), Karl Kerner (chapters 2 and 4) and the reviewers of the different articles for helpful comments and suggestions for improving them and thereby the entire thesis.

I am grateful for having such good colleagues and friends helping me through the darkest nights, backing me up or just letting me work or recover. Thanks to my family, Jakob, Ada, Bo and Birgit for their support, patience and understanding. They helped me to balance work, sickness and private life.

Tingvoll, September 2016

Matthias Koesling

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Variations in nitrogen utilisation on conventional and organic dairy farms in Norway

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Submitted to Agricultural Systems

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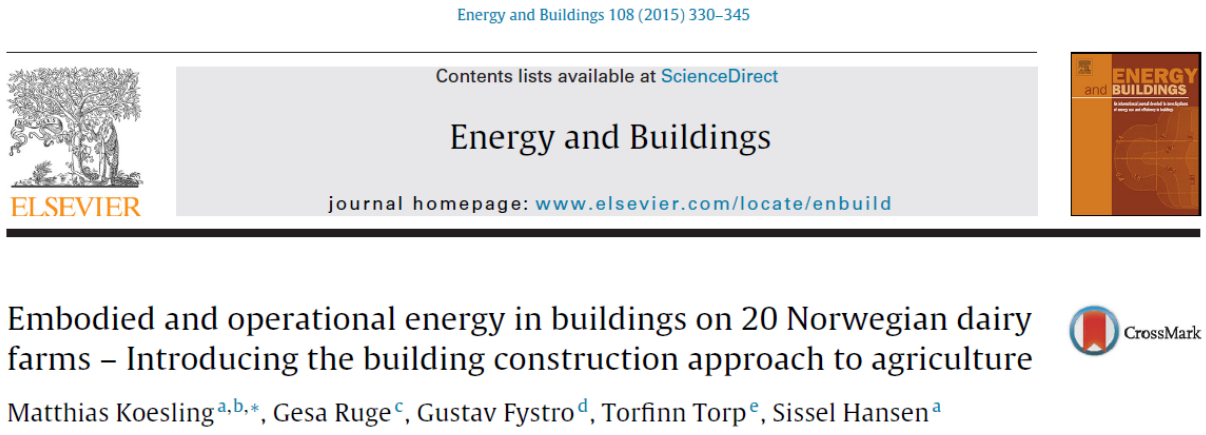

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Embodied and operational energy in buildings on 20 Norwegian dairy farms – Introducing the building construction approach to agriculture

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Variation in energy utilization in dairy farming on conventional and organic Norwegian dairy farms and possibilities for improvement

Matthias Koesling, Sissel Hansen, Maximilian Schüler

Submitted to Journal of Environmental Management

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List of abbreviations

con	conventional
DF	dairy farm
DS	dairy system
ECM	Energy corrected milk
$\varepsilon_{i\text{-}pDF}$	Energy intensity on purchased inputs on the dairy farm
$\varepsilon_{i\text{-}pDF+Infra}$	Energy intensity purchased inputs and infrastructure on the dairy farm
$\varepsilon_{i\text{-}all}$	Energy intensity on all inputs
F	farm
ha	hectare
kg	kilogram
MJ	Mega Joule
N	nitrogen
N_{iall}	Net N-input dairy system
N_{iDF}	N-intensity on purchased inputs on the dairy farm
$N_{iDF+OFs}$	N-intensity on purchased inputs on the dairy farm and off-farm N-surplus
N_{iDS}	N-intensity on all inputs on the dairy system
OF	off-farm
org	organic

1 General introduction

1.1 Environmental sustainability in dairy farming

In industrialized countries, dairy is an important part of farming, and milk is an important part of the human diet. After World War II, an increase of agricultural production was an important means to enhance the food supply all over Europe. This production increase was based on the use of fertilisers, pesticides, concentrates, and on the replacement of man- and horsepower by machinery, using fossil fuels and electricity instead of own fodder for horses. Livestock breeding resulted in cows with higher milk yields, a development which still is in progress.

While this development increased the production per farmer, area and cow, the oil-crisis in the 1970s led to a critical view on society's increasing dependency on the limited amount of fossil energy sources. But not only the dependency on fossil energy received increasing awareness in those years, the issue of environmental pollution was also firmly placed on the agenda. These developments resulted in well-known publications such as "The Limits to Growth" (Meadows et al., 1972). In regard of agriculture, the publication by Pimentel et al. (1973) was one of the first focusing on the dependency on fossil energy, and was followed up by many other studies. The report on "Our Common Future" (Brundtland et al., 1987) not only describes an increasing environmental decay, but highlights the possibility of a sustainable use of global resources. Using resources sustainably is seen as a possibility for economic growth and a pathway for coming generations. While it may be easy to agree upon that we need a more sustainable agriculture, it seems to be more difficult to define sustainable agriculture and measure its degree of sustainability. This uncertainty has resulted in more than 70, somehow differing, definitions (Pretty, 1995). Many agree on three important dimensions: environmental, economic and social sustainability.

In this study, different co-authors and I focus on the utilisation of nitrogen and primary energy on dairy farms in terms of their importance for environmental sustainability. Nitrogen, regardless of whether it originates from artificial fertiliser, manure or biological nitrogen fixation, can be a water pollutant, leading to eutrophication and acidification on a local (e.g. Beek et al., 2003) and global scale (e.g. Doney et al., 2007). The use of energy is not only important in terms of the direct use of electricity and diesel on farm, but also with regard to all primary energy needed to produce all inputs from cradle to farm gate, called embodied energy[1]. The use of renewable energy is also included in this study, because saving renewable energy in agriculture can reduce the use of fossil energy in other sectors. Analysing the use of nitrogen and energy is an essential part of a life cycle assessment (LCA). In recent decades, many LCAs have been conducted for dairy farming in Europe (e.g. Yan et al., 2011). These studies are important for understanding the impact of dairy farming on the environment. Different indicators are used to describe environmental and economic performance, using different models (Calker et al., 2008; Halberg et al., 2005a, 2005b; Lien et al., 2007; Meyer-Aurich, 2005; Pelletier et al., 2008; Pimentel et al., 2005; Pretty et al., 2005; Roedenbeck, 2004; Werf and Petit, 2002). The models have different focuses (farm optimisation, marketing or administration), and due to their varying complexity the demand for input data differs. Models can help to improve the sustainability of farms by reducing nutrient surpluses (Granstedt, 2000). This is particularly efficient when a nutrient accounting system is used in combination with fertilisation schemes and improvements by specific on farm advice (Halberg et al., 2005b). For the farmer it is important that the farm is understood as a system, also taking farm economy into consideration when improving environmental performance. Otherwise, it is possible that an improvement in one area can move problems to another area (Kohn et al., 1997). Such models have been developed in many countries, but no such model linking sustainability assessment and management advice exists in Norway for dairy farming.

Dairy farming in Norway is under an ongoing structural change, with the number of dairy farms having been reduced from 2002 to 2012 by 45 % to 10,335 farms. At the same time, the number of organic dairy farms increased by 26 % to 344 farms. The number of dairy cows on all dairy farms in Norway increased by 50 % to 23, while the number of dairy cows per organic dairy farm was nearly doubled to 26. The overall average milk yield per cow in Norway increased from 6,190 kg per year in 2002 to 7,303 kg in 2012[2], whereas yields on organic farms increased by 26 % from 5,240 kg to 6,600 kg in the same period. The increasing size of organic farms can be partially explained by the tendency of farms with small cultivated area and herd size to give up certified organic farming, while mainly larger farms converted to organic farming (Koesling et al., 2008). Flaten and Lien (Flaten and Lien, 2009; Flaten, 2002) conclude that farm expansions lead to more expensive buildings. In the project

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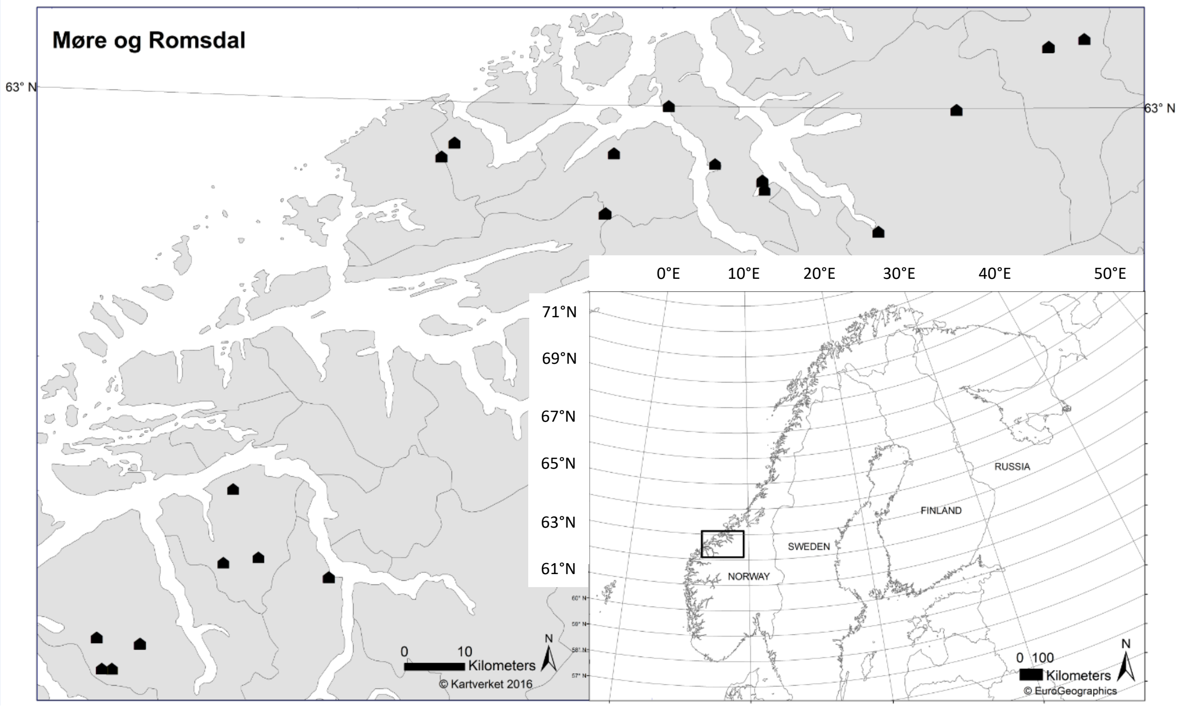
[1] In German the term *Graue Energie* is used.

[2] https://medlem.tine.no/aktuelt/nyheter/husdyrkontrollen/_attachment/297302?_ts=13d92495db0

Environmental and economical sustainability of organic dairy farms and in this thesis, the focus is on dairy farms in Møre og Romsdal County because these farms contribute to about 85 % of the added value from agriculture in this county. Results from the study are expected to be used in other parts of the country, because the conditions in Møre og Romsdal are comparable to those in other agricultural areas in Norway.

Figure 1.1. Map of Northern Europe, the County of Møre og Romsdal and location of the 20 farms.



It is important to understand the effects of such structural changes on the utilisation of nitrogen and energy. The changes are influenced by different goals of conventional and organic farmers (Koesling et al., 2008) and are supported by regulations, and market dynamics. While the farms are increasing in size, the Ministry of Agriculture in a White paper pointed out that especially small scale farms contribute to environmental goods (Ministry of Agriculture and Food, 1999).

While many studies have been conducted on the utilisation of nitrogen and primary energy on dairy farms in other European countries, there is little knowledge about these issues in Norway. Since Norwegian farming is characterised by a short growing season, and due to the ongoing structural change, it is important to understand how nitrogen and energy are utilised. Furthermore, are there differences between conventional and organic farms? What is the variation within each mode of production? These questions cannot be sufficiently answered by results from other countries, since they are hardly valid under Norwegian conditions.

1.2 Research objectives

Based on the specific conditions in Norway, the objectives of this study were to analyse if the utilisation of nitrogen and energy in dairy farming in Norway can be improved to strengthen the environmental sustainability of dairy production. If this is the case, the study should also investigate if different improvement strategies are necessary on conventional and organic farms.

Based on the overall objectives, the specific objectives of the three papers were:

- **Variations in nitrogen utilisation on conventional and organic dairy farms in Norway**

  To determine the most important variables influencing the nitrogen intensities for organic and conventional, commercial dairy farms.
- **Embodied and operational energy in buildings on 20 Norwegian dairy farms – Introducing the building construction approach to agriculture**
  - To implement the building construction approach and to estimate the embodied energy in building envelopes on dairy farms.
  - To investigate if the amount of embodied energy per cow place and nutritional energy in sold milk and meat is equal for different barns and modes of production.
  - To indicate variables leading to a high or low amount of embodied energy in building envelopes on dairy farms.
  - To investigate if the amount of operational energy is related to variables that are important for embodied energy in buildings.
- **Variation in energy utilization in dairy farming on conventional and organic Norwegian dairy farms and possibilities for improvement**
  - To investigate if the energy intensity for producing food in regard of production mode differs,
  - To investigate if embodied energy in machinery and buildings has an important impact on energy intensity,
  - To examine if different solutions for different modes of production have to be chosen to reduce energy intensities.

1.3 Structure and content

The introduction is followed by the research objectives addressed by the three articles, presented in chapters 3, 4 and 5, respectively. I am the first author for all three articles, which are either published by or submitted to peer-reviewed journals (page ix). The layout for these chapters is adapted to the different journals in regard of tables and figures, and thus the layout is not consistent throughout the thesis. The reference list does not follow after each scientific article, but is merged into one reference list for the entire thesis. The numbering of the chapters, tables and figures in the articles has been replaced by a consistent numbering for the thesis as a whole. For this thesis, parenthetical referencing (Harvard referencing) was chosen. Thus, the references in chapter 4 are not in line with the journal Energy and Buildings, which requests numbered references.

Some additional results are given in chapter 5, to support the synthesis and the general conclusions for the entire work that are presented in chapter 6.

An English summary is given in chapter 7 and a German summary in chapter 8. The references for the entire thesis are in chapter 9.

The different co-authors, contributing to the work in chapters 2, 3 and 4 are mentioned under the heading of the chapters. The structure of the articles is comparable, with an abstract, introduction connecting the research to other studies, the objectives and material and methods, before the results are presented and discussed, followed by the conclusions.

Chapter 2, “Variations in Nitrogen Utilisation on Conventional and Organic Dairy Farms in Norway “, had the aim to find the important variables for nitrogen intensity on conventional and organic dairy farms in Norway. Nitrogen intensity is the amount of nitrogen from inputs used to produce one kg of nitrogen for human consumption in milk and meat. The use of nitrogen is analysed using a life cycle assessment approach from cradle to farm gate, and includes not only the use of nitrogen on the dairy farm, but also the off-farm area needed to produce imported feed such as concentrates and roughages. In most comparable studies, efficiencies are used, while intensities have the advantage that they easily allow to point out the contribution of each input and compare different farms.

To be able to calculate the amount of embodied energy in buildings, **chapter 3** “Embodied and operational energy in buildings ” describes the approach we used and introduced to agriculture. The materials and methods section is used to give a broad overview over different approaches so far used for agricultural buildings, mentioning their advantages and weaknesses. By using the building construction approach, it was possible to reduce the workload for calculating the amount of embodied energy in the envelope of agricultural buildings while being flexible enough to reflect the different buildings found on the farms.

Based on chapter 4, it was possible to carry out the work presented in **chapter 5**, “Variation in energy utilization in dairy farming on conventional and organic Norwegian dairy farms and possibilities for improvement”. Comparable to chapter 3, we used a life cycle assessment approach from cradle to farm gate. In this study we focused on all primary energy needed to produce, directly and indirectly, all inputs used for dairy production. The main inputs for intermediate consumption, machinery and buildings were included. The results were used to find the important variables influencing the energy intensity and to give different recommendations for conventional and organic dairy farms on how to reduce the energy intensities.

1.4 Personal work and contribution from others

The work with the doctoral education and thesis was planned as an important part in the project “Environmental and economical sustainability of organic dairy farms” (EnviroMilk). I contributed to planning and writing the application. The project was managed by Dr. Sissel Hansen, who also was my local supervisor. In addition to the work with the doctoral thesis, I had an important part in planning and conducting data collection on the farms, and accessing farm data from other sources. I was also responsible for data storage and preparing the data for further use. Parts of the three articles, presented in chapters 2 to 4, have been presented by me in preliminary versions at different conferences and meetings. Feedback and discussions with the supervisors and the project partners have been used to improve the articles. I was first author for all three articles and thus planned the content, objectives and structure. The co-authors were important discussion partners and gave comments on how to conduct calculations, and set up tables and figures. For all articles, Dr. Sissel Hansen has been important for the entire process, by discussing, controlling, and guiding my work.

In **chapter 2** (variations in nitrogen utilisation on conventional and organic dairy farms), farms are analysed on how they utilized nitrogen to produce milk and meat. Ass. Prof. Marina Azzaroli Bleken has been working for many years on this topic and her experience and her approach to how to describe the intensity of nitrogen as “nitrogen cost” (Bleken and Bakken, 1997; Bleken et al., 2005) was important for developing the use of “nitrogen intensities”.

Nitrogen intensities were chosen instead of cost in this project, where the phrase “cost” could mislead to an economic interpretation as also the economic performance on the farms was analysed. Analysis of nutrient content in soil and fodder was conducted by Eurofins Norsk Matanalyse (www.eurofins.no).

Chapter 3 on embodied and operational energy in buildings on 20 Norwegian dairy farms, was a necessary step to be able to calculate the amount of embodied energy in agricultural buildings with a less time demanding approach than used by for example Dux et al. (2009), but much more precise than using the modular approach from ecoinvent. Dunja Dux and Dr. Thomas Nemecek at Agroscope in Switzerland helped by introducing me to mass material approach. Based on literature, I prepared and conducted the building construction approach developed by (Kohler, 1994) to agricultural buildings on the farms, and thus introduced the approach to agriculture. Ass. Prof. Gesa Ruge, University of Canberra in Australia helped to calculate the amount of embodied energy in buildings. Dr. Gustav Fystro and Dr. Sissel Hansen contributed to planning the registration and discussing the results, while Torfinn Torp helped to conduct the statistics.

To analyse energy utilization in dairy farming in **chapter 4**, Maximilian Schüler contributed with his experience in life cycle assessment and modelling to find data and conduct the calculations for all different inputs used directly and indirectly on the farms. I discussed the results with him and Dr. Sissel Hansen. Dr. Alem Kidane worked on the different ingredients for the different formulations of the concentrates used on the farms to find the countries of origin, yields and relevant fertilizing level.

In **chapter 5** some additional results on the use of dairy farm and system area and economy on the farms are presented, and used for the synthesis and general conclusions. The presentation of the economic results is based on calculations of Dr. Ola Flaten.

2 Variations in Nitrogen Utilisation on Conventional and Organic Dairy Farms in Norway

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2.a Abstract

The objective of this study was to analyse the important variables influencing the nitrogen (N) intensities for ten organic and ten conventional commercial dairy farms. N-intensities, defined as the amount of kg N used per produced kg N output at farm gate, were calculated. The N-intensities allow to quantify the share of different inputs to the intensities and to easily compare the composition of different inputs on different farms. For the study data were used from 10 certified organic and 10 conventional, commercial dairy farms in Norway from 2010 to 2012.

On average, the organic farms produced milk and meat with lower N-intensities, and had a lower N-surplus per hectare than the conventional ones. On conventional farms, on average 5.7 ± 1.1 kg N from purchased inputs were used to produce 1.0 kg N in milk and meat, giving an N-intensity of 5.7 ± 1.1 (2.7 ± 0.7 on organic farms). The N-intensity for the entire conventional dairy system was 7.3 ± 1.0. N-fertilisers (43 %) and concentrates (30 %) accounted for most of the N input. On organic farms, the average N-intensity for the dairy system was 5.2 (± 1.2). Biological nitrogen fixation (BNF) contributed on organic farms with 32 % and concentrates 36 % of the N-input. The N-surplus was on average 222 ± 55 kg N ha^{-1} on conventional and 89 ± 26 kg N ha^{-1} on organic farms.

The level of the N-intensity for N-purchase on the dairy farm and off-farm N-surplus as input and N in milk and meat gain as output, was mainly determined by two variables. First, N-intensity increased with increasing amounts of fertilizer N per hectare. Second, an increased share of imported feed N decreased the N-intensity. The share of imported feed N is calculated as N-import by feed, divided by all N-purchase.

An increase of N-input per hectare increased the amount of N-output in milk and meat per hectare, but on average only 11 % of an increase was utilised as N-output. Thus an increase in N-input mainly contributed to higher N-intensities and higher N-surpluses per hectare. While on conventional farms, N-intensities based on purchased inputs decreased with increasing milk yield per cow, organic farms had lower N-intensities than the conventional, irrespective of milk yield.

2.b Keywords

Efficiency; life cycle assessment; nitrogen intensity; meat; milk.

2.1 Introduction

Livestock contributes worldwide to 34 % of human protein supply (Schader et al., 2015), but the livestock sector is one of the significant contributors to environmental problems from local to global scale (Steinfeld et al., 2006). Thus reducing N losses is mentioned as a way to reduce these problems and as an important factor for improving efficiency and productivity in agriculture (Gerber et al., 2013). N-losses have also an important local effect on the environment, mainly on the quality of surface and ground water. Thus, the environmental impact of N should be assessed both in relation to unit of product and hectare of agricultural area used (Haas et al., 2001; Oudshoorn et al., 2011).

In the last 20 years, many studies on N-balances, N efficiencies and Life Cycle Assessments (LCA) have been carried out on dairy farming in Europe. Some of these studies include comparisons of organic and conventional farms (Cederberg and Flysjö, 2004; Cederberg and Mattsson, 2000; Dalgaard et al., 1998; Haas et al., 2001; Nielsen and Kristensen, 2005; Thomassen et al., 2008; Werf et al., 2009).

In Norway, there is an ongoing structural change in dairy farming. Between 1992 and 2012, the number of dairy farms decreased by about 60 % to 10,890. The result is an increase of average farm area. In the mentioned period, the average herd size increased by 87 % to 23 cows per farm (Tine, 2013). At the same time, average milk yields per cow increased from 6,304 kg to 7,240 kg per year (Tine, 2013). These changes are welcomed by the Ministry of Agriculture and Food, which assumes that bigger farms can utilise economies of scale (Ministry of Agriculture and Food, 2005) and thereby ensure a more efficient production.

In this study, N-intensities are used as an indicator for the resource use on dairy farms. The N-intensity is the amount of nitrogen used by inputs for the production of 1 kg of nitrogen for human consumption. Intensities are favourable to present the influence of each input (Bleken et al., 2005), which is not possible using efficiencies (the inverse of intensities, see for example Meul et al. (2009)). As efficiencies, intensities are dimensionless.

The objective of this study was to determine the most important variables influencing the nitrogen intensities for organic and conventional, commercial dairy farms.

2.2 Materials and Methods

2.2.1 Farm selection and description

The study was based on farm data from 10 certified organic and 10 conventional, commercial dairy farms in the county of Møre og Romsdal in central Norway for the calendar years 2010 to 2012. The selected farms differed in number of dairy cows, milking yield, farm area per cow, fertilisation and forage to concentrate ratio to reflect variations found in the county.

The county is mainly located in a coastal area around 63°N and is quite humid. The selected farms are spread throughout the county, with some at the coast and some in the valleys further inland. The coldest monthly average near the coast is 2 °C, and in the valleys -5 °C, the warmest 14 °C and 15 °C, respectively. The annual precipitation varies from 1000 to 2000 mm, and is fairly evenly distributed throughout the year, with highest values near the coast (Dannevig, 2009).

The outdoor grazing period is usually not more than three months for dairy cows and four for heifers. They graze on fully and surface cultivated land, native grassland and rangeland. In the indoor season, the animals are mainly fed farm-grown roughages and imported concentrates. On cultivated area, only grass and grass-clover leys are grown, cereals can be used as a cover crop when establishing new leys and are harvested as silage.

2.2.1.1 System boundaries

We defined **dairy farm** as the area where purchased N (N-content of consumed products) is used for dairy cows and other cattle. The system boundaries for the **dairy system** include dairy farm area and cattle herd, in addition to off-farm area for growing imported roughages and concentrate ingredients. We applied a farm gate trade balance supplied with estimated biological nitrogen fixation (BNF) and atmospheric deposition. For this study, only farms with dairy production as their main enterprise were selected. However, several farms had some sheep or horses, or sold silage. The area and nutrients used for grazing and roughage production for other non-dairy animals on the farm or for export, were excluded from our calculations.

2.2.1.2 Farm areas

The Norwegian Agriculture Agency distinguishes between three categories of utilised agricultural area: fully cultivated land, surface cultivated land, and native grassland (Fig. 2.1). On **fully cultivated land** it is possible to plough, use manure and mineral fertilisers and harvest with machines, and thus achieve the highest yields. On **surface cultivated land**, ploughing is not possible and yields are lower than on cultivated land. **Native grassland** can only be used for grazing and has the lowest yields of the three categories. To reflect the different levels of possible yields on the three areas, we multiplied each hectare of fully cultivated land with 1, of surface cultivated land with 0.6 and of native grassland with 0.3. To designate the sum of the areas, including the above-mentioned “yield potential factor” for the three categories of farmland, the term weighted farm area is used.

Free rangeland consists mainly of native woodland or alpine vegetation, and can only be used for grazing. The area of free rangeland is not included in the calculation of dairy farm area. To show contribution to dry matter (DM) production, we calculated how much cultivated area would be needed to produce the DM uptake on free rangeland (Table 2.1).

The area used to produce fodder or fodder-components for concentrates purchased by the farm is named **off-farm area** to indicate that this area is not owned by the farm itself, but is essential for the farm’s dairy production and thus part of the dairy system (DS). Off-farm area can be in the vicinity of the farm, in other parts of the country or other countries.

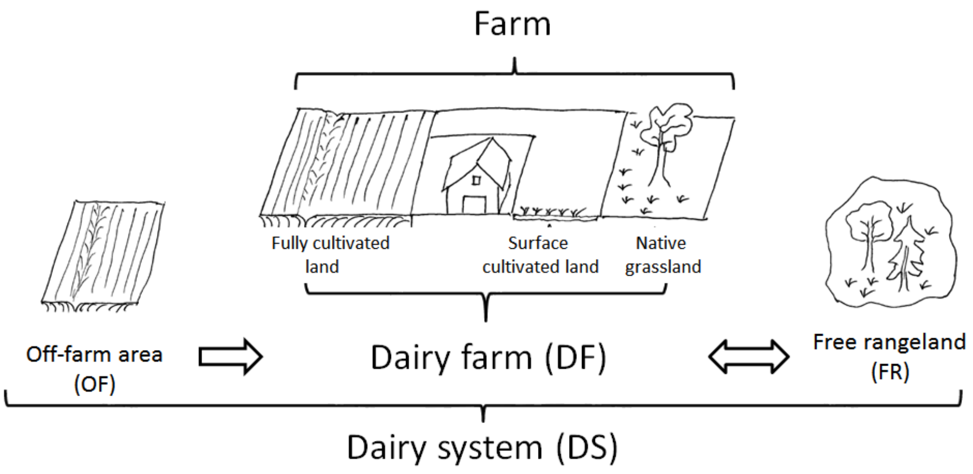

Fig. 2.1 Different categories of areas for the dairy farm and the dairy system.

2.2.1.3 Farm data and sources

Data from the 20 farms were collected for the calendar years 2010 to 2012 to calculate average annual values, thus reducing the influence of weather variations on yields and production. Each year, data were collected after spring cultivation, first and second cut and in autumn after the growing season.

The information collected included farm area, livestock numbers, tillage operations, yields and number of grazing days on different areas, purchased concentrates, bedding material, fertilisers, pesticides, im- and export of roughages and manure, amount and type of manure applied. Farm visits were used to introduce the data collection forms and prepare farm maps.

The main characteristics of the farms are shown in Table 2.1. Only one of the 20 farms had no access to free rangeland. Of the entire feed uptake by cattle, 5.9 % were estimated to come from free rangeland on conventional and 8.1 % on organic farms.

Table 2.1 Main characteristics of the dairy farms.

Parameters	Units[a]	Conventional	standard deviation	Organic	standard deviation
Farms	n	10		10	
Fully cultivated land	ha	26.8	13.6	33.0	23.7
Surface cultivated land	ha	0.3	0.4	0.2	0.5
Native grassland	ha	13.6	22.7	11.3	14.7
Dairy farm area (DF); weighted[c]	ha	31.1	19.6	36.5	26.3
Off-farm area	ha	28.2	16.7	24.9	20.2
Dairy system area (DS)	ha	59.3	34.6	61.4	46.3
Share of energy uptake on free rangeland in relation to entire feed uptake	%	5.9	3.9	8.1	8.2
Cows per farm	cows farm^{-1}	29.5	16.4	29.4	17.3
DF Stocking rate	cows ha^{-1}	0.9	0.3	0.8	0.2
DS Stocking rate	cows ha^{-1}	0.5	0.1	0.5	0.1
Liveweight milking cow	kg	570	40	545	75
Milk delivered per milking cow[b]	kg ECM cow^{-1}	7 301	582	5 490	1 679
Milk delivered per DF area	kg ECM cow^{-1}	7 206	2 205	4 590	1 097
Milk delivered per DS area	kg ECM cow^{-1}	3 646	594	2 776	514
DF Area per milk delivered	m^2 kg^{-1} ECM	1.5	0.6	2.3	0.6
DS Area per milk delivered	m^2 kg^{-1} ECM	2.8	0.6	3.7	0.7
Milk fat	%	4.09	0.25	3.89	0.22
Milk protein	%	3.39	0.08	3.28	0.12
Replacement rate	%	41.4	10.0	33.6	8.0
Diesel use DF	l ha^{-1}	179	68	96	36
Working hours on farm	h farm^{-1}	4 014	507	3 802	736
Return to labour per recorded working hour	€ h^{-1}	14.7	6.8	14.5	4.5

[a] Units of parameters are given. Numbers for participating farms are means for average of calendar years 2010-12 with standard deviation.

[b] Milk delivered includes milk sold to dairy and private use

[c] Weighted area = Fully cultivated land + 0.6 Surface cultivated land + 0.3 Native grassland

In addition to costs and income figures, accounting data included quantities and type of product. For the inputs containing nitrogen, we used the declaration of contents when available, or the standard nutrient content (NORSØK, 2001). The DM and N contents of concentrates were calculated from information on the formulations for the different types given by the Norwegian Agricultural Purchasing and Marketing Cooperation.

The nitrogen concentration (kg N kg^{-1} DM) for on-farm roughages was estimated from analysis of on-farm silage. In 2010 and 2011, silage samples were taken from 1st and 2nd cut and analysed for dry matter and protein content. These values were used for silage on farm. The average values for organic and conventional farms were used as estimates for the N-content in imported silage. In years with good weather conditions, some farms can take three cuts of fodder. Nevertheless, the 1st and 2nd cut represent the bulk of available winter fodder. Seeds and medicines were excluded because of their small impact (Cederberg and Mattsson, 2000). The different products included and the average annual values for nitrogen per hectare are presented in Table 2.2. The production on free rangeland in the table is an exception. Because nitrogen was not actively supplied for the production of feed on free rangeland, the values are the calculated nitrogen in milk and meat gain produced on free rangeland. This amount is both an input but also an output.

Table 2.2 Amount of nitrogen per dairy farm (DF) hectare in annual inputs and outputs. Average values and standard deviation are shown for group of conventional and organic farms. For nitrogen, the inputs and outputs are in kg nitrogen per dairy farm hectare. For sums (s), balances (b) and N-intensities, the formulas are given.

		conventional		organic		
	Index and formula	average	std. dev.	average	std. dev.	t-test[a]
N-inputs		[kg N ha^{-1} DF]				
N-purchase dairy farm (DF)	I_a					
Concentrates	I_{aa}	93	36	48	11	**
Roughages	I_{ab}	6	9	11	7	n. s.
Fertiliser	I_{ac}	131	33	3	10	***
Imported manure	I_{ad}	3	9	5	7	n. s.
Bought animals	I_{ae}	1	1	0	1	n. s.
Sawdust and straw	I_{af}	1	1	1	1	n. s.
N-purchase DF	$sI_a = \sum_{n=a}^{f} I_{an}$	235	68	69	19	***
Biological N-fixation	I_b	27	23	43	18	n. s.
Atmospheric N-deposition	I_c	4	1	4	1	n. s.
N-surplus on off-farm area (OF)	I_g	39	16	18	5	**
Feed N-import	$Feed_N = I_{aa} + I_{ab}$	99	42	59	11	***
All N-inputs DF	$sI_b = sI_a + I_b + I_c$	265	66	115	27	***
Net purchase DF	$nI_f = sI_a - O_{manure}$	234	68	69	19	***
Net purchase DF and OF N-surplus	$nI_g = sI_a + I_g - O_{manure}$	273	83	86	22	***
Net input dairy system (DS)	$nI_{all} = sI_b + I_d + I_g - O_{manure}$	305	82	134	27	***
Free rangeland, N produced in milk and meat gain	I_d	2	1	1	2	n. s.
N-outputs		[kg N ha^{-1} DF]				
Sold milk and private use	O_{milk}	38	11	24	6	**
Weight gain	O_{weight}	8	2	5	1	**
Meat gain	$O_{meat} = O_{weight} \times 0.53$	4	1	3	1	**
Manure export	O_{manure}	0	1	0	0	n. s.
Sum output (milk and meat gain)	$sO_{mm} = O_{milk} + O_{meat}$	43	12	26	6	**
Net output without production free rangeland (FR)	$nO_{mm} = O_{milk} + O_{meat} - I_d$	39	12	24	7	**
N-balances dairy farm		[kg N ha^{-1} DF]				
Balance, purchase DF	$b_p = sI_a - O_{milk} - O_{weight} - O_{manure}$	192	58	42	18	***
Balance, all inputs on DF	$b_{all} = sI_b - O_{milk} - O_{weight} - O_{manure}$	222	55	89	26	***
N-intensities		[kg N (kg N)$^{-1}$]				
N-intensity purchase DF	$N_{iDF} = nI_f / sO_{mm}$	5.7	1.1	2.7	0.7	***
N-int. purchase DF and OF N-surplus	$N_{iDF+OFs} = nI_g / sO_{mm}$	6.6	1.2	3.3	0.8	***
N-intensity all input DS	$N_{iDS} = nI_{all} / sO_{mm}$	7.3	1.0	5.2	1.2	***
N-intensities without free rangeland (FR)						
N-intensity purchase DF - FR	$Nn_{iDF} = nI_f / nO_{mm}$	5.9	1.2	2.9	0.8	***
N-int. purchase DF and off-farm N-surplus - FR	$Nn_{iDf+OFs} = nI_g / nO_{mm}$	6.8	1.3	3.6	0.9	***
N-intensity all input DS - FR (in- & output)	$Nn_{iDS} = (nI_{all} - I_d) / nO_{mm}$	7.6	1.0	5.5	1.3	**

[a] significant at level
*** < 0.001; ** < 0.01; * < 0.05

2.2.2 Farm status

2.2.2.1 Feed demand, grazing uptake, harvest and weight gain

The feed demand for all animals on the farm was calculated for each year as net energy demand. The cattle were grouped as calves, heifers, bulls, dry cows and cows. Feed demand was calculated for each group based on breed, condition, weight and milking yield using specific values for Norway (Olesen et al., 1999) (Table 2.2). We assumed that the amount eaten corresponded to the energy demand. The energy demand from on-farm roughage was calculated as the total energy demand minus energy taken up from concentrates, imported roughage, free rangeland and on-farm grazing. Based on the energy demand (FEm), the DM uptake for the different cattle groups was calculated by dividing the energy demand (FEm) by the energy content (FEm kg^{-1} DM) of the different feeding stuffs (Table 2.3). For each farm, the energy content for on-farm roughages was calculated from fodder analyses and for concentrates, it was based on amount of purchased concentrates and the corresponding energy content. Grazing uptake from farm pasture and free rangeland was calculated by multiplying days for each group on area by estimated daily feed uptake based on their energy demand given in Table 2.3.

The farmers registered the number of animal within each group, grazing area and grazing period. Farmers reported if dairy cows were on grazing area day and night or only during daytime between milking. Based on (Steinwidder et al., 2001) we assumed that cows have 5/8 of the daily grazing intake during daytime and 3/8 at night.

The DM harvestable (grazable) yield on grazed farm area was calculated by dividing the total energy uptake (FEm) for all groups from grazing by the energy content (FEm kg^{-1} DM). Assuming a loss of 44 % of grazable yield (Steinshamn et al., 2004), we multiplied DM uptake by 1.8 to get the grazable yield. Accounting for stubbles by adding dry matter grazing intake multiplied by 0.2, the total above ground dry matter (DM_{TAG}) on grazing farm area was estimated as 2.0 times DM grazing intake.

The harvested DM yield was calculated by dividing the estimated DM uptake by 0.85, to account for storage losses of 15 % after harvesting. DM harvestable yield was calculated by multiplying harvested DM yield with 1.3 (Steinshamn et al., 2004), and to also include stubbles with 1.4 for total above ground matter (DM_{TAG}).

Table 2.3 Energy demand for cattle and energy concentration in feed.

	Energy demand/day		**Average daily weight gain**	**Energy content**	
			Norwegian Red	conventional	organic
	FEm (kg milk)$^{-1}$	FEm^{f}	kg animal^{-1}	FEm (kg DM)$^{-1}$	FEm (kg DM)$^{-1}$
milking cows^{a}					
maintenance		5.10^{b}			
milk yield [kg day^{-1}] < 20	0.44^{b}				
20 - 30	0.45^{b}				
> 30	0.47^{b}				
dry cows per "dry"-day^{a}		6.60^{b}			
calves < 6 month		2.22^{b}	0.6^{b}		
calves 6-12 month		3.85^{b}	0.6^{b}		
bulls > 12 month		6.53^{b}	0.9^{b}		
heifers 12-18 month		4.49^{b}	0.6^{b}		
heifers > 18		5.38^{b}	0.6^{b}		
On farm roughage (average for group)				0.86^{c}	0.83^{c}
Concentrates (average for group)				0.91^{d}	0.88^{d}
Grazing farm area				0.90^{e}	0.90^{e}
Grazing free rangeland				0.85^{e}	0.85^{e}

[a] Values for 580 kg liveweight (Norwegian Red). To adjust for other liveweight the demand of FEm day-1 was multiplied by the average liveweight of cows on farm [kg] and divided by 580 [kg].
[b] Olesen et al., 1999.
[c] Calculated on feed samples from farm.
[d] Calculated on declaration from concentrates, bought in group.
[e] Based on results from earlier grazing trials and investigations in outlying fields (Gustav Fystro personal communication).
[f] FEm is defined as net energy of 1 kg barley and corresponds to 6.9 MJ.

For both grazed and harvested area, we chose a ratio for below ground clover dry matter (DM$_{BG}$) to clover DM$_{TAG}$ of 0.5, based on and Høgh-Jensen et al. (2004). This value is within the range for N-fixing forages (0.4 ± 50 %) from IPCC (1997).

Some farms enlarged their herd in the course of the study period. Thus, they kept cow calves they otherwise could have sold. To account for this strategy, we use weight gain for the herd instead of using weight of sold animals. To calculate the weight increase of the dairy herd, we multiplied the number of animals on farm with the number of animal days in each feeding group with the assumed average daily weight gain for the group (Table 2.3). Meat was calculated as 53 % of liveweight (Olesen et al., 1999).

2.2.2.2 Nitrogen fixation and atmospheric deposition

Biological nitrogen fixation (BNF) was calculated in the same way for grazed and harvested farm area using equation 1.

$$BNF = (DM_{TAG} + DM_{BG}) \times Cl\,\% \times N\,\% \times P_{fix}\,\% \tag{2.1}$$

where

DM_{TAG}	total above ground DM [kg]
DM_{BG}	below ground DM = $DM_{TAG} \times 0.5$ [kg]. This value is in line with IPCC (1997)
Cl %	percent of clover in grass clover yield (%). Estimated by the farmers before the first and second cut. Pictures showing grassland with different amount of clover where used to improve the estimate.
N %	3 % N-content, according to Høgh-Jensen et al. (2004) and in the line with the findings of Hansen et al. (2014).
P_{fix} %	95 %. We assumed the percentage of N in plant from BNF to be 95% (Høgh-Jensen et al., 2004), because the farms with a higher share of clover had a low fertilization rate.

The amount of atmospheric nitrogen deposition was calculated as the total dairy farm area, based on data from the Norwegian Agricultural Authority, multiplied with 2.94 kg N ha^{-1} and year, the regional value of atmospheric N deposition (Aas et al., 2011).

2.2.3 Functional units

Milk includes both fat and protein in varying amounts. To compare milk on the basis of the energy content, the amount of milk mass can be standardized to a kg of energy corrected milk (*ECM*) (Sjaunja et al., 1991) based on its fat, protein and lactose content:

$$\begin{aligned} ECM\,[\text{kg}] = {} & milk\,[\text{kg}]\,((38.3\,fat\,[\text{g kg}^{-1}] + 24.2\,protein\,[\text{g kg}^{-1}] + 16.54\,lactose\,[\text{g kg}^{-1}] \\ & + 20.7)\,/\,3{,}140) \end{aligned} \tag{2.2}$$

Norwegian full-cream milk is sold with 3.9 % fat and 3.3 % protein (Norwegian Food Safety Authority, 2015). To calculate the nitrogen content of milk and meat we divided the protein content by the conversion factor 6.38 for milk and 6.25 for meat (FAO, 1986). For cattle, on average 2.4 % of liveweight is estimated to be nitrogen (Andrew et al., 1994).

The farmers in our study sold milk and animals for slaughter or as live animals. The methods of dealing with these co-products have an impact on the results (Cederberg and Stadig, 2003; Kraatz, 2009), but in this article we use a system expansion and no allocation was needed. The functional unit in this study is 1.0 kg nitrogen for human consumption in the product of delivered milk and meat gain. 1.0 kg nitrogen comprises to 193.3 kg of milk or 30.3 kg of meat or any other combination summing up to 1.0 kg nitrogen.

2.2.4 Nitrogen in- and outputs, N-balances and N-intensities

Purchased N-input (SI_a) on the DF was the sum of concentrates, roughages, purchased fertiliser, imported manure, bought animals, sawdust and straw (Table 2.2 and Eq. (2.3)).

$$sI_a = I_{aa} + I_{ab} + I_{ac} + I_{ad} + I_{ae} + I_{af} = \sum_{n=a}^{f} (I_{an}) \tag{2.3}$$

The N-balance on purchased N on DF (b_p) was calculated by subtracting the output of milk, weight gain and exported manure from the purchased N-input (Table 2.2 and Eq. (2.4)).

$$b_p = sI_a - O_{milk} - O_{weight} - O_{manure} \tag{2.4}$$

The N-balance for the roughage-producing off-farm area was estimated, based on local field trials, fertilisation data and information from the local extension service, to be 80 kg N ha^{-1} for conventional farms and 0 kg N ha^{-1} for organic farms including atmospheric deposition and N-fixation by clover. Roughages are normally sold from stockless farms with no or low input of animal manure, and thus N-surpluses are lower than on dairy farms. The DM roughage yield per hectare off-farm area was assumed to equal the calculated average harvested yield from the farms in our investigation (4200 kg DM ha^{-1} for conventional and 2940 kg DM ha^{-1} for organic farms). The off-farm area (ha) needed to produce roughage was calculated by dividing the amount of imported roughage (kg DM) by the assumed harvested yield (kg DM ha^{-1}). The off-farm area needed (ha) was multiplied by the estimated N-surplus (kg N ha^{-1}) to get the N-surplus from off-farm roughage production.

For yields and fertilisation levels in Europe, we used literature values (Korsaeth and Eltun, 2000; Watson et al., 2002; Øgaard, 2014). For products from other continents, such as soybean meal, rape seed meal, rape beans, molasses, beet pulp and maize, yield and nutrient enrichment were taken from the MEXALCA report (Nemecek et al., 2011). For one kg fresh mass of product for each ingredient, the land occupation (m^2) and N-enrichment (kg N-equivalents) were taken from the report. The N-enrichment (kg N kg^{-1} product) for each ingredient was multiplied by the amount of the product in the bought concentrates (kg) and summed up to get the entire N-surplus (kg N) to produce concentrates. The off-farm area needed for each product was calculated by multiplying the mass of product (kg) for each ingredient with the land occupation (m^2 kg^{-1}).

The N-surpluses (kg N ha^{-1}) from growing off-farm roughages and the different products in concentrates were summed up and then divided by the dairy farm area to give the N-surplus on off-farm area (I_g).

Nitrogen uptake on free rangeland was calculated as the sum of feed uptake (FEm) divided by energy content (0.85 FEm kg^{-1} DM) and multiplied by the estimated nitrogen content for free rangeland (0.011 kg N kg^{-1} DM, Gustav Fystro personal communication, based on judgement from earlier investigations).

The N-intensities are dimensionless and calculated as a quotient with the mentioned net N-input as dividend and with the N output from net milk and meat gain (nO_{mm} or sO_{mm}) as divisor (for calculations see Table 2.2).

2.2.5 Statistics

For statistics the software R®,[3] was used in combination with RStudio®,[4]. The software was used for linear regressions, t-tests and correlation matrices. Correlation was calculated as Pearson’s r and matrices were conducted to see how variables were linked to the different N-intensities and farm N-balances. The matrices allow in addition to see the correlations between variables. The matrices had to be conducted separately for conventional and organic farms, because different variables were significant, some variables had different strength and direction and some variables were only significant due to the differences between the two modes of production. For descriptive statistics as mean, standard deviation and figures, Microsoft® Excel® 2013 was used.

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[3] Version 3.2.4, www.r-project.org

[4] Version 0.99.893, www.rstudio.com

2.3 Results

2.3.1 Contribution of purchased inputs on produce and N-intensity

Increased nitrogen input from purchase increased N-output of delivered milk and meat gain (sO_{mm}, $R^2_{all} = 0.71$, $P < 0.001$, Fig. 2.2). Only 11 % of an increase was utilized as N-output, resulting on average in higher N-intensities when net N-purchase on dairy farms increased. On organic farms, there was no clear trend.

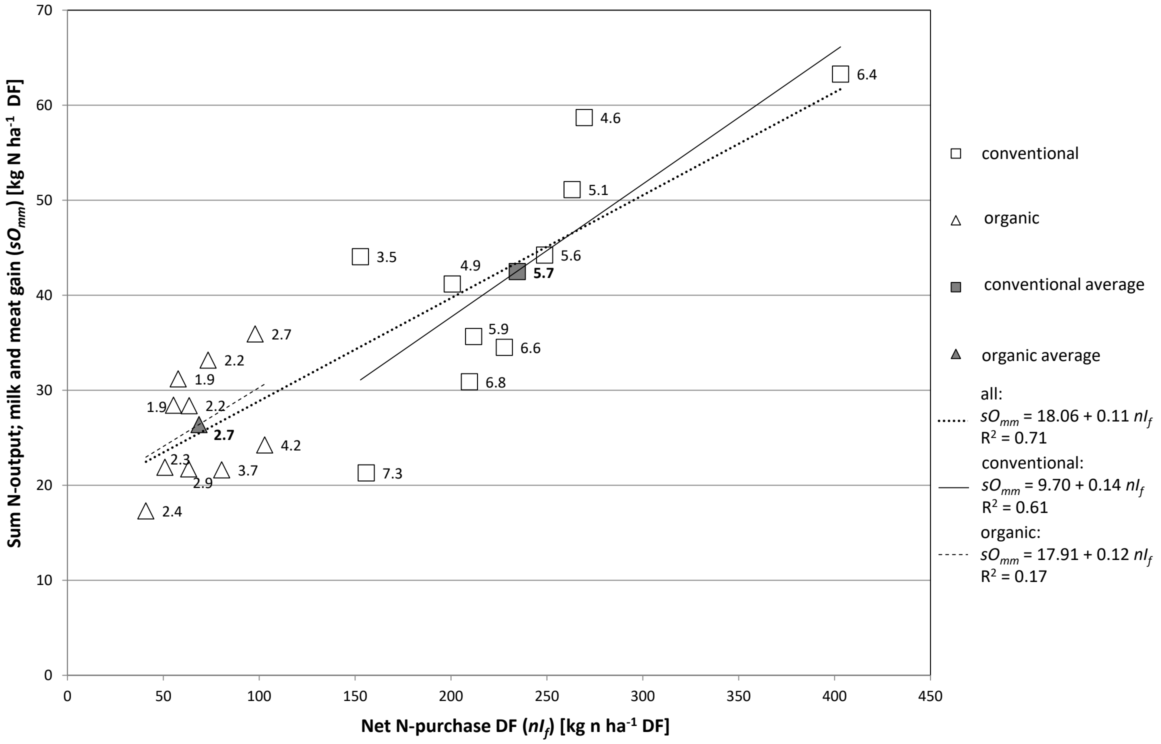
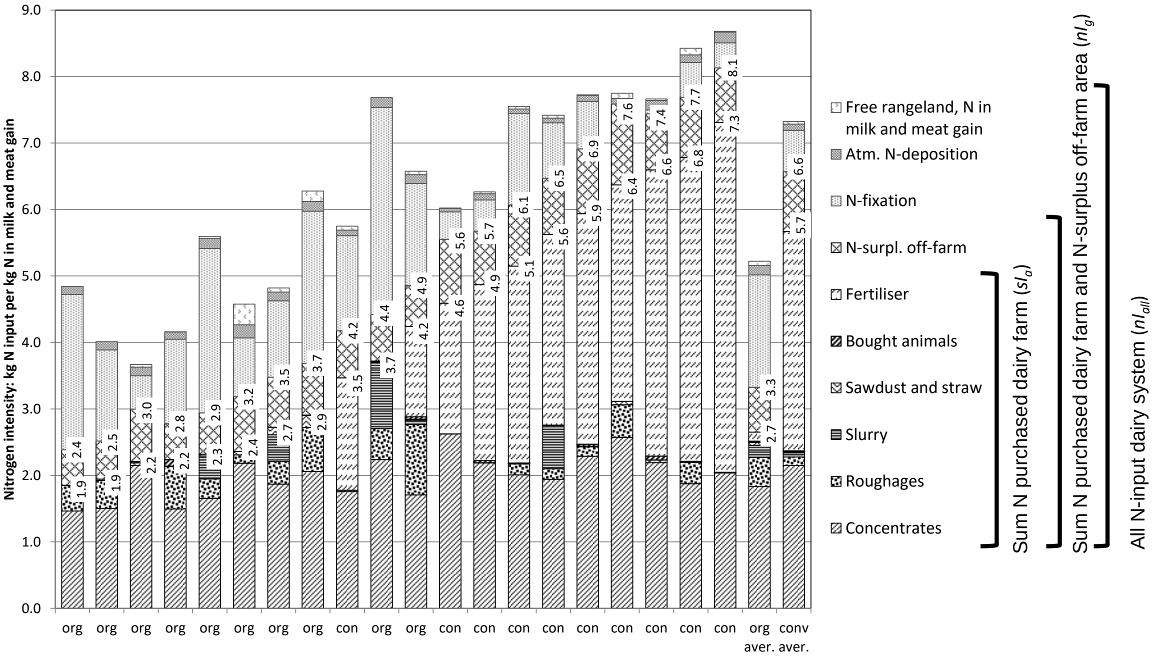


Fig. 2.2 Net N-output in milk and meat gain (sO_{mm}, vertical axis) in relation to the nitrogen input from purchase per dairy farm hectare (nI_f, horizontal axis). The labels indicate the values for nitrogen intensity (N_{iDF}) based on purchase.

Fertiliser accounted for the largest part of the purchased N-input on conventional farms, 56 %, and the farms that used fertiliser had higher N-intensities N_{iDF} (Table 2.2) than the farms that did not. Concentrates represented a significant share of the nitrogen input, with an average amount of 93 ± 36 kg N ha^{-1} DF on conventional and 48 ± 11 kg N ha^{-1} DF on organic farms. On organic farms, the N-surplus on off-farm area for producing concentrates and roughages (I_g) contributed on average 20 % of the sum of net N-input from purchased DF plus OF N-surplus (nI_g). For conventional farms, this figure was 13 %. The N-balances (b_p and b_{all}) were positive on all farms, and thus always resulted in an N-surplus. The N-intensities calculated were significantly lower on the organic dairy farms than on the conventional farms, regardless of whether production on free rangeland was included or not. An exception was the N-intensity on all inputs without free rangeland (Nn_{iDS}), where the difference was not significant.



Milk yield [ECM cow^{-1} year^{-1}]	7091	8261	7506	4377	5121	2977	7331	4076	8649	5516	7713	9161	8349	8166	9354	8437	7927	7812	7117	7733	5997	8271
N_{iDS-FR}	4.8	4.0	3.8	4.2	5.7	6.2	5.1	7.1	6.0	7.7	6.9	6.0	6.4	7.8	7.7	7.8	8.3	7.8	9.2	8.7	5.5	7.6
$N_{iDF+OFs-FR}$	2.4	2.5	3.1	2.8	3.0	4.6	3.7	4.3	4.4	4.4	5.1	5.6	5.8	6.3	6.8	6.9	8.2	7.6	8.5	8.1	3.6	6.8
N_{iDF-FR}	1.9	1.9	2.3	2.2	2.4	3.4	2.9	3.4	3.7	3.7	4.5	4.6	5.0	5.3	5.9	6.0	6.9	6.7	7.5	7.3	2.9	5.9

Fig. 2.3 The amount of N from different inputs to produce 1 kg N in delivered milk and meat gain (left axis) on conventional (con) and organic (org) farms.
The lower label in the bars displays the N-intensity N_{iDF}, the upper label displays the N-intensity $N_{iDF+OFs}$, and the entire bar represents the N-intensity N_{iDS}. The legend shows the inputs and their grouping.
The farms are sorted by increasing N-intensity N_{iDF}. Under the table the annual milk yield per cow for each farm and N-intensities minus production of N in milk and meat gain on free rangeland are presented. (For indices and calculations see Table 2.2.)

Organic farms had on average an N-intensity N_{iDF} of 2.7 ± 0.7 with milk yields between 2977 and 8261 kg ECM cow^{-1}year^{-1} (Fig. 2.3). The conventional farm with the lowest N-intensity

N_{iDF} (3.5) had a milk yield above the average and an N-fixation per hectare (63 kg N ha^{-1} DF), which was more than twice the average of the conventional farms (27 kg N ha^{-1} DF), and used the lowest amount of fertiliser (75 kg N ha^{-1} DF) among the conventional farms. Some farms produced an important share on free rangeland. For these farms the N-intensities where higher for the production without the contribution on free rangeland.

2.3.2 Nitrogen intensity and milk yield

The milk yield varied less on the conventional (7100 to 9400 kg ECM cow^{-1}year^{-1}) than on the organic (3000 to 8300 kg ECM cow^{-1}year^{-1}) farms (Fig. 2.4). Compared to the organic farms, the average N-intensity $N_{iDF+OFs}$ on the conventional farms was nearly twice as high (Table 2.2). On conventional farms the N-intensity $N_{iDF+OFs}$ decreased with increasing milk yield (Fig. 2.4; $R^2 = 0.41$, $P < 0.01$). On organic farms, there was no indication that the N-intensity $N_{iDF+OFs}$ was influenced by the milk yield.

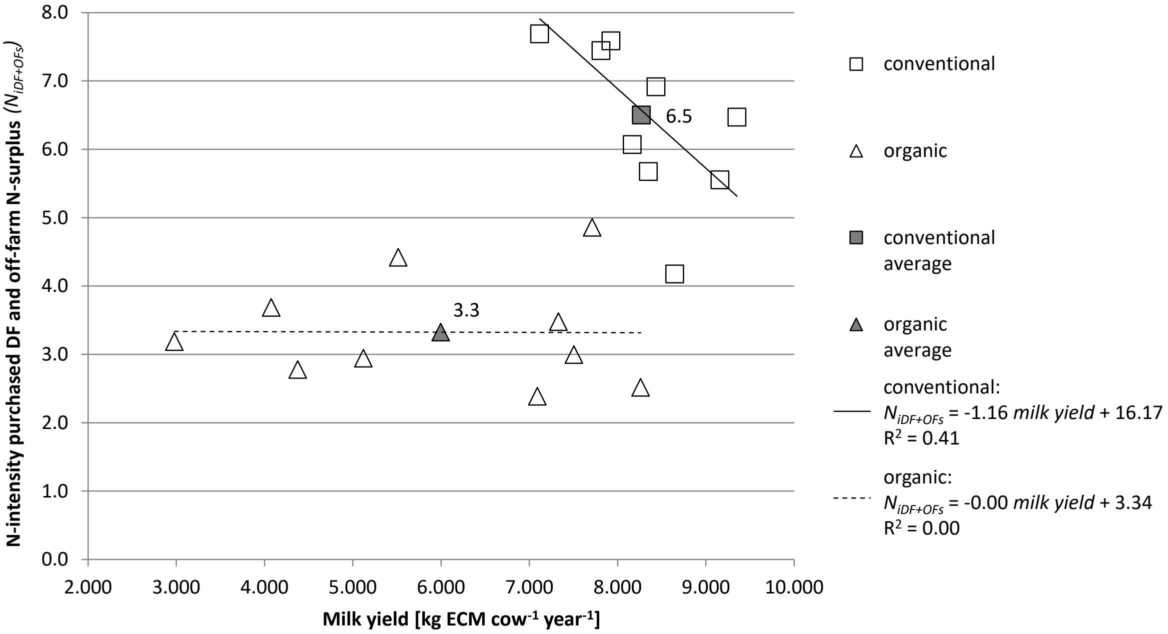


Fig. 2.4 N-intensities $N_{iDF+OFs}$ (vertical axis) versus annual milk yield per cow (horizontal axis). Values are given for conventional and organic farms, the average for each group and with linear regression for the two groups. (For indices and calculations see Table 2.2.)

2.3.3 Correlation between variables

For conventional farms, the variables milk yield per cow and clover percent in DM yield were found to be negatively correlated with the N-intensities N_{iDF} and $N_{iDF + OFs}$, implying that farms with higher milk yields per cow and higher clover percent in grassland had lower N-intensities N_{iDF} on purchased N (Table 2.4). For organic farms, the harvestable DM yield was negatively correlated with the N-intensities N_{iDF} and $N_{iDF + OFs}$, while clover percent in DM yield was found to be negatively correlated with all three N-intensities.

Table 2.4 Correlation matrix for selected variables. Correlation calculated as Pearson's r. Correlation values are only presented when the significance level was below 0.05.

	Milk yield per cow [kg ECM/n]	Harvestable yield [kg DM ha^{-1} DF]	Clover percent [% in DM harvestable yield]	N-fertiliser [kg N ha$_1$ DF]	Balance, purchase DF [kg N ha^{-1} DF]	N-intensity purchase DF	N-intensity purchase DF and off-farm N-surplus	N-intensity all input DS
Conventional farms								
Balance, purchase DF [kg N ha-1 DF]				0.907 ***	1			
N-intensity purchase DF	-0.659 *		-0.666 *			1	0.995 ***	0.943 ***
N-intensity Purchase DF and off-farm N-surplus	-0.648 *		-0.692 *			0.995 ***	1	0.934 ***
N-intensity all input DS	-0.661 *					0.943 ***	0.934 ***	1
Organic farms								
Balance, purchase DF [kg N ha^{-1} DF]		-0.703 *	0.648 *	0.699 *	1	0.882 ***	0.872 **	
N-intensity purchase DF		-0.821 **	0.747 *	0.726 *	0.882 ***	1	0.992 ***	0.829 **
N-intensity purchase DF and off-farm N-surplus		-0.844 **	0.680 *	0.682 *	0.872 **	0.992 ***	1	0.804 **
N-intensity all input DS			0.866 **			0.829 **	0.804 **	1

Significant at level
*** < 0.001; ** < 0.01; * < 0.05

2.3.4 Variables influencing N-intensities

To find the important variables influencing the N-intensities, the results from the correlation matrices were used to preselect variables. Regressions with different variables were tested for all twenty farms and separately for each group. A linear regression (Eq. (2.5)) resulted in a high coefficient of determination (Fig. 2.5) for the N-intensity for purchase on dairy farm (N_{iDF}, Table 2.2) for all 20 farms.

$$N_{iDF} = 8.42 - 6.55\ Imp\ Feed_{N\text{-}share} \tag{2.5}$$

with

$$Imp\ Feed_{N\text{-}share} = Feed_N\ sI_a^{-1} \tag{2.6}$$

The variable $Imp\ Feed_{N\text{-}share}$ in Eq. (2.6) reflects the share of entire N-import by feed in relation to entire N-import by purchase. $Feed_N$ (N imported by feed) is calculated as the sum of imported N by feed, both N in concentrates and roughages. The entire N from purchase (sI_a) is the sum of all imported N by purchase to the dairy farm. This regression has a coefficient of determination of 0.90 for all 20 farms ($P < 0.001$), but R^2 is only 0.63 ($P < 0.01$) for conventional and 0.82 ($P < 0.001$) for organic farms. The coefficient of determination increased when including N-fertiliser per DF ha (I_{ac}, Table 2.2) (Eq. (2.7)).

$$N_{iDF} = 6.88 - 4.90\ Imp\ Feed_{N\text{-}share} + 0.007\ I_{ac} \tag{2.7}$$

This regression has a coefficient of determination of 0.91 for all 20 farms ($P < 0.001$). The R^2 is 0.84 ($P = 0.002$) for conventional and $R^2 = 0.84$ ($P = 0.001$) for organic farms. Thus, Eq. (7) predicts well the N-intensity N_{iDF} for dairy farms in this study, irrespective of production method. Based on the regression, the N-intensity N_{iDF} is lower when a higher share of the entire N-import by purchase is from the entire N-import by feed. Also a lower use of purchased fertiliser N reduces the N-intensity N_{iDF}.

The conventional farm with the lowest N-intensity N_{iDF} (3.5) achieved the average milk and meat production of conventional farms (44 kg N ha^{-1}) and purchased the least N fertiliser per hectare (75 kg N ha^{-1}). For this farm the observed N-intensity was much lower than predicted by Eq. (2.7).

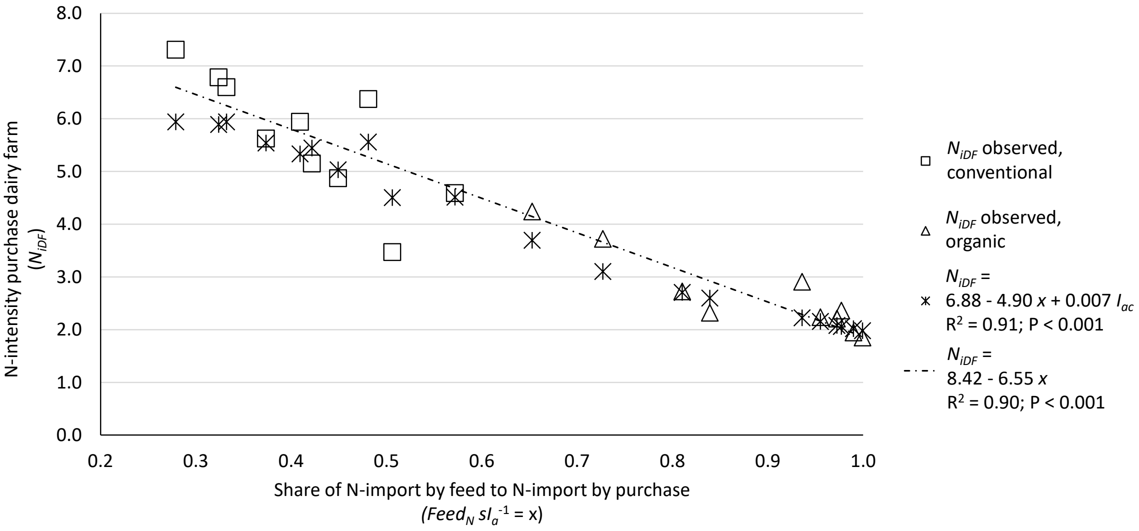


Fig. 2.5 N-intensity N_{iDF} (vertical axis) versus N-import by feed as share of all N-import by purchase (horizontal axis).
Values are given for conventional (con) and organic (org) farms, with linear regression (Eq.(2.5)) and predicted values (Eq. (2.7)). (For indices and calculations see Table 2.2.)

2.4 Discussion

Despite a high variation within the two groups of farms, general statements on the benefits of conventional or organic mode of production are possible, albeit simplifications. A higher production of milk and meat per farm area was found on the conventional farms, which is in line with the results from Ponti et al. (2012) for Northern Europe.

The higher production on the conventional farms in this study was based on larger amounts of purchased N and resulted in higher N-intensities per product and higher N-surpluses on dairy farm area (Table 2.2). Such high N-surpluses are found to lead to high costs for society (Sutton et al., 2011). Feeding a high share of concentrates and importing most of the protein-rich ingredients contributes to placing Norway among the top ten net importers of N per capita world-wide (Oita et al., 2016, supplementary material). High N-intensities and high N-surplus per ha are leading to significant emissions of reactive nitrogen.

When comparing milk production per area, it is important to which area is used for the calculation, dairy farm or dairy system area. The organic farms delivered 4590 ± 1097 kg milk ha^{-1} related to the dairy farm area (Table 2.1), which is 64 % of the amount on conventional farms (7206 ± 2205 kg ha^{-1} DF). Relating milk production to the entire area for feed production of the dairy system (DS), the organic farms delivered 2776 ± 514 kg ha^{-1} DS, or 76 % of the production of the conventional farms (3646 ± 594 kg ha^{-1} DS). This underlines that it is important to include the area of the entire DS when the area productivity shall be compared.

On conventional farms, N-fertiliser was highly positively correlated with increased N-surplus on the dairy farm area (Table 2.4). Surprisingly, a regression showed no significant positive effect of increased N-fertilisation on estimated DM yield per DF area. This finding and a high N-surplus raises the questing if many conventional farmers do not only use traded N-fertilisers to increase yields, but also as an insurance to grant high yields (Sheriff, 2005; Øgaard, 2014). Due to the high N-surplus on many conventional dairy farms, it should be possible for them to reduce the use of N-fertiliser without reducing yields. This is also suggested by Groot et al. (2006) as the best strategy to increase N-efficiency on dairy farms in the Netherlands.

Organic farms had lower N-intensities N_{iDF} because the N-import consisted mainly of feed, while N-fixation was an important nitrogen source for the overall N-supply. An increase in roughage yields on organic farms could lower their N-intensities further.

2.4.1 N-intensities and N-surpluses of dairy farm and dairy system

Our results on N-intensities N_{iDF} for conventional (5.7 ± 1.1) and organic (2.7 ± 0.7) dairy farms are comparable with most studies in Europe referred to in the introduction, although the difference between the N-intensities between conventional and organic in our study is higher. Our findings are comparable to those of Dalgaard et al. (1998) under Danish conditions. Cederberg and Mattsson (2000) also found an N-surplus (198 kg N ha^{-1} for conventional and 65 kg N ha^{-1} for organic dairy farms) close to our results (b_P: 192 kg N ha^{-1} for conventional and 42 kg N ha^{-1} for organic dairy farms). None of the studies we found, except those of Godinot et al. (2014) and Bleken et al. (2005), discuss or include the N-intensity and N-surplus on off-farm area for imported feed. In our study, the N-intensities N_{iDS} which includes all purchased nitrogen and biological nitrogen fixation, atmospheric deposition, production on free rangeland and off-farm n-surplus were 7.3 ± 1.0 on conventional and 5.2 ± 1.2 on organic dairy farms.

In the mentioned studies, the amount of the different inputs is presented, but their influence on N-intensities (the reciprocal to N-efficiencies) is not discussed. Based on the findings from

Nadeau et al. (2007), a cow needs about 3.3 kg N from feed to produce 1 kg N in milk, resulting in an N-intensity of 3.3 for the cow itself. N-intensities above and below this figure for the entire dairy farm are thus mainly a result of feed production on the dairy farm and utilisation of imported N to produce milk and meat. Due to low fertiliser rates, low N-surplus and feed being the main N-import, the N-intensities on organic farms are close to the results presented by Nadeau et al. (2007). On conventional farms, feed production with a high N-surplus (b_p) and a high share of import of N-fertiliser results in higher N-intensities. When the N-surplus on a dairy farm is high, importing feed will not increase N-intensities as long as the N-surplus on off-farm area is lower than on the dairy farm. However, importing N-fertiliser (having a lower trophic level) without increasing yields, will result in higher N-intensities.

Some farmers make a large effort to have a balanced fodder composition (energy and protein), to create optimal conditions for good animal health, to improve N-utilization of their farm manure, to reduce losses from field to feed table, improve soil drainage and to reduce soil compaction. These are all factors that can affect N-intensities. Because all farms are in the same geographical region, the variation in farm management is likely more important than variation in soil type and climate for the variation in obtained N-intensities.

For the production on a farm, low N-inputs result in low yields. Since intensities are calculated kg N-input kg N-output, the low N-inputs will result in in low N-intensities and be perceived as environmentally beneficial. The same problem arises when calculating efficiency. To overcome this problem it is important to include the production per area (White, 2016) in addition to intensities or efficiencies to find good solutions for the environment.

2.4.2 Effect of milk yield on N-intensities

Increased production of milk per cow was previously found to be positively correlated with lower N-intensities (Børsting et al., 2003; Kristensen et al., 2015; Nadeau et al., 2007). This effect was also shown for conventional farms (Fig. 2.4) in this study. The reasons for the reduced N-intensities on the conventional farms seem to be compounded. First, the share of feed needed for a cow’s metabolism per litre milk produced decreases with increasing milk yield. Second, imported concentrates are produced with low N-surplus. For the conventional farms in our study with high N-intensities, an import of concentrates produced with a relatively low N-surplus results in lower calculated N-intensities for the dairy farm. Growing soybeans in Brazil results, for example, in an N-surplus of 27 kg N ha^{-1} and maize from France in 108 kg N ha^{-1} (Nemecek et al., 2011). These N-surpluses are quite low compared to the average N-surplus for all N inputs (b_{all}, Table 2.2) found for the conventional farms in this study, 222 ± 55 kg ha^{-1} DF.

In contrast to the conventional dairy farms, organic dairy farms had low N-intensities, regardless of whether milk yields were 3000 or 8300 kg ECM $cow^{-1}year^{-1}$. As a general explanation for low N-intensities on organic farms we found the high share of imported N by feed in relation to all N imported. The imported feed was in addition produced with low N-surplus.

These N-intensities without the production on free rangeland are only for some farms higher than the N-intensities presented in Fig. 2.3. This underlines the important contribution from grazing free rangeland for some farms. We estimated that an average of 5.9 % of the entire feed demand for conventional and 8.1 % for organic farms was from free rangeland. On the organic farm with the longest annual grazing period on free rangeland, we estimated the energy uptake to be 27.0 % of the entire energy demand. Without free rangeland, more cultivated or off-farm area would have to be used if the same amount of milk and meat should be produced.

Some organic farmers had dairy cows from traditional breeds, which are smaller and have lower milking yields than the main commercial breed, Norwegian Red. This is the main reason for the lower average live weight of cows on organic farms (Table 2.1).

The calculation of N-surplus on off-farm area abroad was based on data from Nemecek et al. (2011). They mention that modelling simplifications and uncertainty have to be considered when data are used. Better data on production of ingredients for imported feed, separately for conventional and organic production, would allow further, in-depth analyses and enable the selection of feed components with lower N-intensities.

2.4.3 Representativeness

In the project, 10 of the 13 dairy farms certified for organic production in the county participated. Thus the organic farms are representative for organic dairy farming. The share of conventional dairy farmers in the study is rather small relative to the total number of such farms in the region. However, since the farms differed in size of agricultural area, number of dairy cows and use of nitrogen fertiliser per hectare, we expect them to be representative for the variation found on conventional farms in the region. We expect that comparable results as found in this study can be found in other countries, if nearly all concentrates are imported and high amounts of N-surplus are found for plant production on conventional farms.

2.5 Conclusions

Based on the data for all 20 farms, the level of nitrogen intensity for N-purchase on the dairy farm and off-farm N-surplus, was mainly determined by two variables. First, the N-intensity increased by increasing the amount of imported fertilizer N per dairy farm hectare. Second, the N-intensity decreased by a higher share of the N-import by feed of all N imported by purchase. For many inputs and outputs there was a high variation within each group, while organic farms had per hectare a significantly lower import of purchased N and a lower output of N in delivered milk and meat gain. N-intensities were also significantly lower on organic dairy farms. This is consistent with other studies. An increased amount of purchased N on the dairy farm area was found to slightly increase the production of N in milk and meat on the dairy farm. An increased milk yield per cow on conventional farms was found to reduce N-intensities, while the N-intensities on organic farms were lower, regardless of whether milk yields were 3000 or 8300 kg per cow and year.

Using N-intensities, defined as N-input divided by N-output, allowed to quantify the share of different inputs to the N-intensities and easily compare farms. The results from different farms can thus be used as bench-marking for other farms and to find ways to reduce N-intensities.

2.6 Acknowledgements

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3 Embodied and operational energy in buildings on 20 Norwegian dairy farms – Introducing the building construction approach to agriculture

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3.a Abstract

Embodied energy in barns is found to contribute to about 10 % to 30 % of total energy use on dairy farms. Nevertheless, research on sustainability of dairy farming has largely excluded consideration of embodied energy. The main objectives of this study were to apply an established model from the residential and commercial building sector and estimate the amount of embodied energy in the building envelopes on 20 dairy farms in Norway. Construction techniques varied across the buildings and our results showed that the variables which contributed most significantly to levels of embodied energy were the area per cow-place, use of concrete in walls and insulation in concrete walls. Our findings are in contrast to the assumption that buildings are similar and would show no significant differences. We conclude that the methodology is sufficiently flexible to accommodate different building design and use of materials, and allows for an efficient means of estimating embodied energy reducing the work compared to a mass material calculation. Choosing a design that requires

less material or materials with a low amount of embodied energy, can significantly reduce the amount of embodied energy in buildings.

3.b Key words

Embedded energy, building material, sustainable farming, farm building construction,
organic farming

3.1 Introduction

The efficient and sustainable use of resources is increasingly important for developments in farming operation and management globally. The focus of early 20th century farming was on the efficient use of land, equipment and workers. This changed with the oil crisis in the 1970s, when the use of non-renewable resources such as oil, gas and coal became a conscious part of farming operational decision making (Pimentel et al., 1973) and attention shifted to increasing food production with reduced negative environmental impacts (Dogliotti et al., 2014b). Worldwide, more than 40 % of all energy use is linked to buildings and they produce one third of greenhouse gas emissions during their entire life cycle (Huovila et al., 2009). In the European Union, the energy consumption of buildings is around 37 % of the primary energy consumption (Pérez-Lombard et al., 2008) and expected to grow (European Parliament, 2003).

Dairy milk production is probably the food type for which most Life Cycle Assessment (LCA) or carbon footprint analysis has been published (Cederberg et al., 2011b) and there are various publications on sustainability in dairy farming (for example Calker et al., 2006; Dalgaard et al., 2006). Nevertheless, even in comprehensive LCA studies the embodied energy in buildings is often not included (for example Gerber et al., 2010; Meul et al., 2007; Yan et al., 2011); (exceptions are Gaudino et al., 2014; Smith et al., 2015), or if it is, this is not made explicit (for example Vries and Boer, 2010). Out of 13 studies on milk production analysed by Yan et al. (2011), only one (Werf et al., 2009) included machinery, and none included buildings. The role of buildings is also omitted from many studies on greenhouse gas emissions from dairy production, as listed by Crosson et al. (2011). There are recurring arguments around why embodied energy is not included in such studies (Harris and Narayanaswamy, 2009). These encompass the following: small influence on overall results (Flysjö et al., 2011), the inclusion of embodied energy is time consuming, there is a lack of data, and that buildings are generally similar and no differences are expected (Cederberg and Mattsson, 2000; Thomassen et al., 2008).

Buildings demand energy both directly and indirectly. Direct energy use occurs during the construction, operating (operational energy), rehabilitation and demolition processes across a building's life cycle. Primary energy is the energy needed to produce the operational energy, including extraction, transformation and distribution losses. Indirect or embodied energy arises from the production of materials and technical installations the buildings are made of (Sartori and Hestnes, 2007). Of these various uses of energy, operational and embodied energy are the most significant, the other energy demand for construction, rehabilitation and demolition is negligible (about 1 %) (Sartori and Hestnes, 2007).

With specific reference to farming, energy consumption in the construction and operation of farm buildings is a notable contributor to overall energy consumption. For example, in Denmark, about 10 % of the overall farm energy consumption was related to buildings for dairy and cattle production (Dalgaard et al., 2000), while for swine production in Iowa, embodied energy in buildings and operational energy accounted for 14 – 27 % of the total energy use (Lammers et al., 2010). Similarly, a study of 50 dairy farms in Switzerland identified that approximately 32 % of overall energy use was linked to farm buildings (Rossier and Gaillard, 2004). These results demonstrate that energy efficient buildings, in regard to both embodied and operational energy, should be considered as an important part of sustainable farming practice locally and globally. Research and literature on embodied energy in buildings has to date largely focused on the residential housing and commercial building sector. The research and analysis of agricultural buildings and the subsequent impact on the agricultural business sector has not been developed to the same degree. In this paper the building constructions approach is used to estimate energy. While there are some limitations with the approach, we consider it to be more practical and to require less work than a mass material calculation. With exception for the mass material approach, we consider that it is more precise than other approaches, when buildings differ in age, materials and appearance.

3.1.1 Approaches to estimating embodied energy in buildings

The amount of embodied energy of a building is estimated for the building's entire lifetime. Usually, it is not known how many years a building will be used and thus the embodied energy of a building is divided by the expected lifetime. Accordingly, the expected lifetime of a building strongly influences the calculations of the annual amount of embodied energy. In the available literature generally, the expected service life of a building is estimated to range from 20 years (Dalgaard et al., 2001; Nielsen and Rasmussen, 1977) to 80 years (Williams et al., 2006). A frequently used assumption is a 50 year expected service life of a building (Dux et al., 2009; Erzinger et al., 2004; Hersener et al., 2011; Nemecek and Kägi, 2007). Irrespective of whether a building is assumed to have a short or long service life, improved knowledge and decision making in relation to the design, construction, and operation of farm buildings will become more important in the future. This is not only in relation to achieving efficient embodied energy within the building envelope for dairy farms, but also in terms of achieving reduced long term operational energy demand and improved functional use.

The analysis of embodied energy in buildings can be done utilising a Life Cycle Analysis (LCA). Either a 'top down' calculation, which breaks down larger components into smaller parts or a 'bottom up' calculation, which builds up the individual parts to the total building, can be utilised. In some instances a combination of both calculation types has also been applied (Nässén et al., 2007). The 'bottom-up' approach, while well suited for the comparison of individual building materials, can lead to an underestimation of embodied energy compared to a top-down approach, because "transport, construction activity, production of machines and service sectors" are not included (Nässén et al., 2007). Additionally, comparisons between individual projects and their calculations are often difficult due to the variability between materials and buildings, or lack of detailed assumptions (Erzinger et al., 2004).

Of the limited research and literature on embodied energy in farm buildings available to date, the 'bottom up' approach is more frequently used (Roer et al., 2013) , particularly in relation to farm barns (see for example Kraatz, 2012; Nemecek and Kägi, 2007; Nielsen and Rasmussen, 1977; Williams et al., 2006). Existing literature frequently combines the calculation of the embodied energy for equipment and buildings with the number of animals or the amount of meat or milk produced. However, this is considered as problematic, especially where the calculation details and assumptions are not clearly articulated (Erzinger et al., 2004) , making it difficult to compare or to adapt the approach to other buildings.

Within the available literature, different bottom-up approaches have been used to estimate the amount of embodied energy in buildings for machinery and livestock. The approaches can be divided into five groups and a summary of key aspects and publications for dairy farming are presented in Table 3.1.

Table 3.1 Bottom-up approaches to estimate the amount of embodied energy in agricultural buildings.

Authors	Buildings (B), Electricity (E)	Results based on	Country	specification	Lifetime building	MJ/m^2 $year^{-1}$	MJ electricity/cow	MJ electricity/kg milk	MJ only barn/cow	MJ building/ kg milk	ruminants: LSU/farm
Mass material calculation											
Nielsen and Rasmussen (1997)	B	materials needed to replace buildings in use for entire agriculture in Denmark	DK		20	-	-	-	4100	0.83	17.3
Refsgaard et al. (1998)	B/E	Nielsen and Rasmussen (2004)	DK	17 conventional farms	20	-	6600 per milk producing unit (1 yearcow + 1 heifer)	0.92	3400	0.48	84.0
				14 organic farms				0.97	3400	0.49	75.3
Dalgaard et al. (2001)	B/E	Nielsen and Rasmussen (2004)	DK		20	-	7961 MJ/cow	conv 1.14 ; org 1.33 per kg ECM	2500	0.33	30.2
Kraatz (2012)	B	model farm with different scenarios to represent future dairy farming, all loose house	DE	cold barn	25	-	-	-	1400	0.18	180 cows
				climate as outside					1400	0.18	
				warm barn					1500	0.18	
				light building					1400	0.18	
Different building constructions											
Audsley et al. (1997)	B	Kohler (1997): about 100 buildings (houses, service and industrial buildings)	NL, CH, DK, UK, FR		80	142 MJ/m2	-	-	-	-	-
Square meter ground-floor											
Rossier and Gaillard (2004)	B/E combined with diesel	35 farms with dairy	CH		actual age	-	-	-	average 12400[a]	2.1 average (0.8-4.5)	22[b]
Williams et al. (2006)	B/E	"representative set of farm buildings"	England and Wales		80	62 MJ/m2	671-1343 MJ/cowplace	0.17 - 0.17 MJ / litre	900	0.13	112[b]
Embodied energy per cow-place											
Nemecek and Kägi (2007)	B	selected examples of buildings, commonly found in CH	CH	tied barn	50	-	-	-	3400	0.49	22
				loose house					4400	0.64	
Schader (2009)	B/E	using ecoinvent 2.0 database	CH	conventional; all buildings	50	-	-	-	5800[a]	1.16[b]	20.3
				conventional; only barn					3700[a]	0.74[b]	20.3
				organic; all buildings					6300[a]	1.26[b]	19.4
				organic; only barn					3400[a]	0.68[b]	19.4
Dux et al. (2009)	B	case study, 59 farms with dairy	CH		50	-	-	-	740-2900 MJ/cow	0.09-0.36 MJ/kg ECM[a]	22
Hersener et al. (2011)	B	case study, 59 farms	CH		50	-	-	-	5700	0.85 MJ/kg milk	22[a]
Fixed combination of materials multiplied by economic value											
Roer et al. (2013)	B/E	three representative farms for three regions	NO		40	-	3900 - 4680 only milking	0.57-0.71 MJ/kg ECM delivered	-	-	20-24
Dogliotti et al. (2014)	B/E	monetary inputs	UY		-	-	-	-	-	-	-

[a] Own calcultaions, using information from the article

[b] Own calcultaions, combining information from the article with official statistics

3.1.1.1 *Mass material calculation*

The amount of total embodied energy is calculated as the sum of the mass of main different construction materials multiplied with the corresponding amount of embodied energy per mass unit. In the studies for Danish dairy production, the amount of the materials needed to replace the actual barns for all cattle production in the entire country is used (Dalgaard et al., 2001; Nielsen and Rasmussen, 1977; Refsgaard et al., 1998). While for Germany, the amount is calculated for possible future barns (Kraatz, 2012). The mass material approach is most precise of the approaches presented and fundamental for all other type of approaches. However, it is demanding (Menzies, 2011). To reduce the workload for calculating the embodied energy, other approaches have been developed.

3.1.1.2 *Different building constructions*

Based on the building analysed, different building constructions are defined (see for example Adalberth, 1997; Kohler, 1994) and used to calculate the amount of embodied energy for the materials found per square meter floor, wall or roof (Kohler, 1994). The amount of embodied energy for the different building constructions per square meter are then multiplied by the total area of each building construction to derive the overall value of embodied energy for a building. Using Kohler’s values for industrial buildings, Audsley et al. (1997) present an ‘upper limit’ for embodied energy for agricultural buildings in different countries, expecting that the value of embodied energy for agricultural buildings is lower than this. Calculating embodied energy of buildings using different building constructions reduces the workload compared to the mass material calculation, but presupposes that the building constructions used for calculations are representative for the buildings analysed.

3.1.1.3 *Square meter ground-floor*

Using square meter ground-floor, Williams et al. (2006) calculated the lowest estimate of embodied energy per cow. The longest building lifetime, 80 years was assumed and their calculations were based on the amount of embodied energy per square meter ground-floor from Audsley et al. (1997). Audsley refers back to Kohler (1994), who calculated embodied energy for 100 buildings (houses, service and industrial buildings) in Switzerland. As building material mainly stone is used and the amount of square meter ground-floor of the barn can be combined with building height. Based on materials and values from life cycle inventories for industrial buildings and the actual age of the buildings, Rossier and Gaillard (2004) calculated in 2004 for 35 existing dairy farms in Switzerland the highest value of embodied energy per cow (12,400 MJ) and litre milk (2.1) compared to all other studies found (see table 1). Based on the results from Rossier and Gaillard, embodied energy in dairy housing accounts for nearly one third of all non-renewable energy use in dairy production. The approach is easy to conduct but the results assume that the buildings analysed are comparable to those used to calculate the amount of embodied energy per square meter ground-floor.

3.1.1.4 Embodied energy per cow-place

Under this approach, the material masses were multiplied with the amount of embodied energy found in the ecoinvent database (Althaus et al., 2007) to calculate an annual amount of embodied energy per cow-place (bedding place for a cow)which can then be used as a functional unit. Both Schader (2009), Nemecek and Kägi (2007), present numbers for tied or loose housing, differing between building materials and some additional building parts. These alternatives are explored in even more detail by Dux et al. (2009). Dux et al. conclude that the amount of embodied energy varies depending on farming, area per functional unit, materials used in construction and materials with high environmental burden (Dux et al., 2009). The modules can be added for other building parts in the barn, for example dried roughage store or silage tower. Data for many modules are available in the ecoinvent database (Frischknecht et al., 2004). Hersener et al. (2011) present the calculations for additional modules. The approach demands little work and will function well as long as the materials used and the appearance of the buildings analysed are comparable to the buildings used for the data in ecoinvent.

3.1.1.5 Fixed combination of materials multiplied by economic value

Roer et al. (2013) used a fixed combination of 60 % wooden products and 40 % construction for barns and multiplied this by the economic value of the barn. They have not published the amount of embodied energy but environmental impacts as global warming potential and conclude that machines and buildings account for 9 % of global warming potential linked to the production of milk. Another possibility to use an economic value is the amortization of machinery and infrastructure as done by Dogliotti et al. (2014a). This approach is easy to conduct but depends on the assumption that the ratio of materials for buildings on different farms is nearly the same and the assumption that the economic value is representative for the amount of materials used.

3.1.2 Electricity as operational energy

The results of studies into the use of electricity as operational energy on dairy farms can be divided into two groups; one group of studies estimates use at about 1 MJ per litre of milk (Dalgaard et al., 2001; Refsgaard et al., 1998; Roer et al., 2012), while another group of studies estimated values ranging from 0.17 (Eide, 2002; Williams et al., 2006) to 0.32 MJ per litre milk (Cederberg and Mattsson, 2000; Meul et al., 2007). A possible reason for the higher estimated electricity consumption could be the inclusion of electricity use in other farm buildings and for other farm purposes. There may also be geographical influences, for example in Norway where electricity is used for cooling of milk, warming of water, heating the milking parlour and sometimes for defrosting of silage. It is not always clear from the studies whether the reported amount of electricity is the amount of electricity used on farm or the amount of primary energy needed for electricity production at grid. The energy source will also influence the results (see table 3.5), such as the low values for hydropower use reported by Cederberg and Mattsson (2000).

3.1.3 Approach

In this paper, a bottom-up approach based on different building constructions was used to calculate the amount of embodied energy which was necessary to produce the building materials in the envelope of barns and other agricultural buildings on dairy farms in Norway, and to point out important variables for the amount of embodied energy. For the purpose of this study, the building envelope is defined as the materials used to construct and enclose the main building parts, such as ground- and intermediate-floors, walls (external and internal), building structure, roof framing and roofing material. Each building is first analysed and different building constructions are defined. The constituent material layers are used to calculate the amount of embodied energy per square meter of the different building constructions (floor, wall or roof) (Dimoudi and Tompa, 2008). The amount of embodied energy for the different building constructions per square meter is then multiplied by the total area of each building construction and summed to derive the overall value of embodied energy for a building. The building constructions approach has been applied to residential and office buildings (Adalberth, 1997; Dimoudi and Tompa, 2008; Erlandsson and Borg, 2003; Kohler, 1994) and is flexible enough to reflect both the individual design as well as different materials used in the envelope of the buildings. It therefore provides a good basis for collection and analysis of comparable data. Farm buildings in particular locations of a country are likely to be constructed of similar materials and use a similar type of construction and assembly due to traditions, suppliers, standardizations and regulations. The approach in this research study was applied to the assessment and calculation of the embodied energy in the envelope of agricultural buildings on 20 Norwegian dairy farms, built from 1899 to 2011.

The embodied energy which was necessary to produce the materials in the envelope of dairy farm buildings can be combined with the amount of primary energy, necessary to produce and transport the electricity, used on farm.

3.1.4 Objectives

This research contributes new findings and understandings of the ways that the embodied energy of buildings can be integrated as an important component of the competitive and sustainable operation of dairy farming. The objectives of the study were to:

- Implement an approach and to estimate the embodied energy in buildings envelopes on dairy farms.
- Investigate if the amount of embodied energy per cow place and nutritional energy in sold milk and meat is equal for different barns and modes of production.
- Indicate variables leading to a high or low amount of embodied energy in building envelopes in dairy farming.
- Investigate if the amount of operational energy is related to the variables that are important for embodied energy.

3.2 Material and methods

3.2.1 Farm selection and characteristics

Out of 1194 dairy farms in ‘Møre og Romsdal’ county in 2009, 10 certified for organic production and 10 conventional farms were selected for this study.

The county ‘Møre og Romsdal’ is located in a coastal area around 63° N and is quite humid. The farms are spread in the county with some at the coast and some in the valleys. The coldest monthly average during a normal year near the coast is 2°C, and in the valleys -5°C. The warmest monthly average near the coast is 14°C and in the valleys 15°C. The annual precipitation varies from 1000 to 2000 mm, with highest values near the coast (Dannevig, 2009). Data on buildings and operational energy use were collected over the period of two years, 2010 and 2011.

The Norwegian Dairy Herd Recording System (Tine, 2013b, 2011) presents data for the region «middle of Norway», including the counties 'Møre og Romsdal', 'Sør-Trøndelag' and 'Nord-Trøndelag'. The conventional farms in the project had more cows and a higher milking yield (Table 3.2) than the average conventional farms in the region (Espetvedt et al., 2013). The milk yield per cow on conventional farms in the project was 41 % higher than on organic farms in the project.

Table 3.2 Characteristics of participating farms and of dairy farms in the middle of Norway.

Characteristic	Units \ Average 2010/11	Conventional in project [b]	Standard deviation	Conventional in region [a]	Organic in project [b]	Standard deviation	Organic in region [a]	All dairy farms in Norway [a]
Farms with dairy herds in Norwegian Dairy Herd Recording System	number	10		2 780	10		119	9 810
Cultivated land	hectare	28.3	12.5	n.a.	34.1	25.0	n.a.	n.a.
Surface cultivated land	hectare	0.4	0.5	n.a.	0.3	0.8	n.a.	n.a.
Pasture	hectare	14.2	23.1	n.a.	12.4	16.5	n.a.	n.a.
Milking cows	number	28.8	15.9	24.1	28.9	17.1	27.6	21.7
Milk production per cow	kg ECM	8 200	700	7 400	5 800	1 700	6 900	7 300
Sold milk	MJ nutritional value	572 000	297 000	n.a.	469 000	397 000	n.a.	n.a.
Sold meat in live and sloughter animals	MJ nutritional value	44 000	39 000	n.a.	33 000	34 000	n.a.	n.a.
Electricity use on farm	MJ	172 000	94 000	n.a.	182 000	153 000	n.a.	n.a.

[a] Norwegian Dairy Herd Recording System (Tine, 2012, 2011)
[b] Farm data and accounts for each farm in the project for 2010 and 2011

3.2.2 Description of barns

Over time, barns have been built or extended to satisfy new needs and regulations, as well as utilising new building materials. A typical design of a barn and its parts is shown in Fig. 3.1. Barns older than 30 years typically had three floors. Manure was stored in the cellar, the ground floor was a tie-stall barn and hay can be stored on the first floor. The basement was built of stone with walls and other constructions of timber. Over the years, the cellar was often reconstructed to store slurry and a silage tower was added.

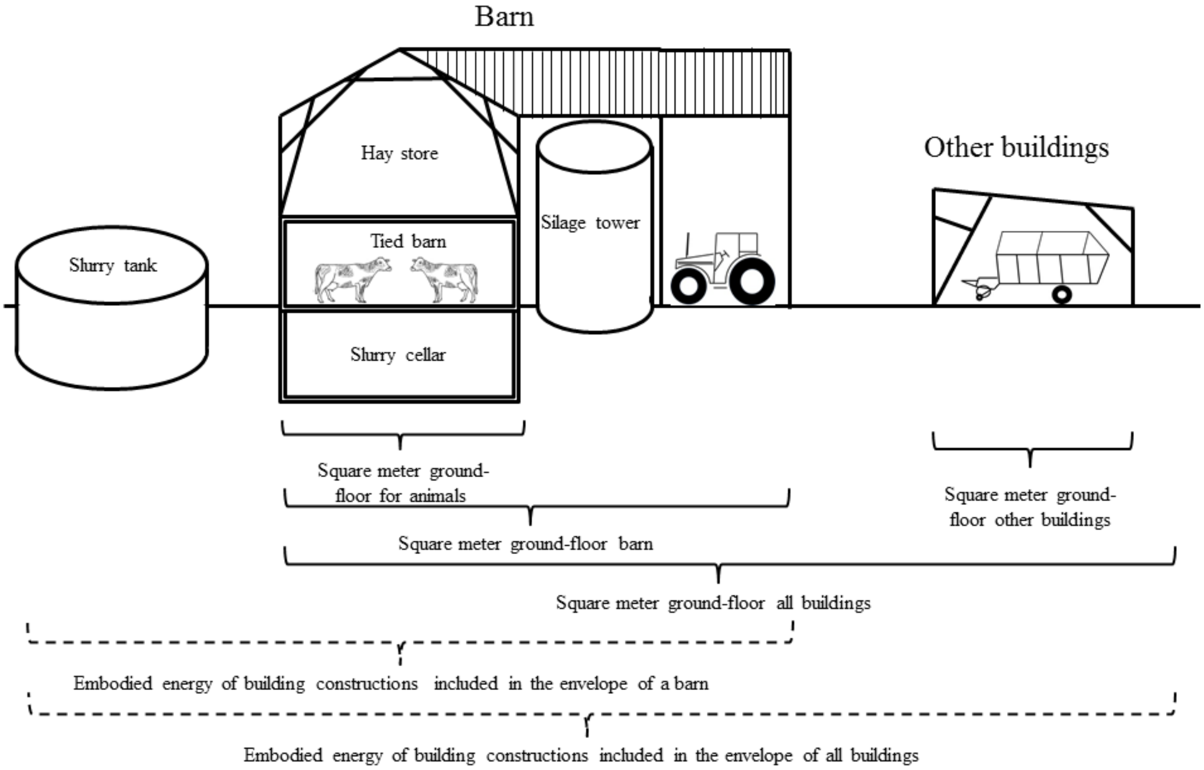

Fig. 3.1 Diagram of buildings for cows and machinery, building parts and ground-floor included in the calculations of square meter ground-floor and envelope.

The barns that were 20 to 30 years old were built with a concrete basement for slurry storage, and the first floor was built as a tie-stall barn. Concrete or timber was extensively used in the insulated barns. Silage towers were a part of the building.

Barns built after the year 2000 were always built as a loose-house, with or without insulation for the dairy cows. Timber, concrete and steel were used as building materials. Some silage towers were included; however, the storing of silage as round-balls outside was established as a common practice. The slurry could be stored either in the basement cellar or in a separate slurry tank outside. Because the use of building materials in a separate slurry tank outside was without any roofing and comparable to a basement cellar, the square meter ground floor of a separate slurry tank was not added to the square meter ground floor of the barn. More detailed information is given in Table 3.2.

Table 3.3 Characteristics of farm buildings in the study.

	First part of barn built	(last) Extension	Cow-places	Additional buildings for youngstock	Additional buildings for machinery	Hay store	Tied housing	Silage tower	Slurry tank or slurry cellar	Ground-floor for cattle	Ground-floor barn	Ground-floor other buildings	Ground-floor all buildings	EE in envelope barn	EE in envelope all buildings	Operational energy (electricity) all buildings
Units	year	year	n	[a]	[a]	[a]	[a]	[a]	st or sc	m^2	m^2	m^2	m^2	MJ/year	MJ/year	KWh/year
	1899	2001	51	-	x	x	-	x	sc	913	1275	95	1369	106873	111005	44158
	1930	1972	36	-	x	x	x	-	sc	469	553	373	926	42077	55858	55650
	1950	2007	32	-	x	x	-	x	sc	481	717	151	868	55708	63365	50171
	1960	2005	44	x	x	x	x	x	sc	547	1328	245	1573	111644	122417	82595
	1960	1993	20	-	x	x	x	x	sc	199	292	127	419	27578	32413	29717
	1960	-	18	-	x	x	x	x	sc	240	500	215	715	46526	54631	27050
	1962	2005	14	-	-	x	x	x	sc	263	505	0	505	47798	47798	28962
	1965	1971	20	-	x	-	x	x	sc	148	293	275	568	35807	42888	16424
	1970	-	27	-	x	x	x	x	sc	225	508	285	793	47117	58887	30618
	1971	2010	34	-	x	x	-	x	sc	752	1158	142	1300	95144	102207	39528
	1978	-	22	-	x	-	x	x	sc	221	540	145	685	39541	45335	20890
	1980	2011	43	x	x	x	x	x	sc	521	985	195	1180	74978	81117	93676
	1981	-	20	-	x	-	x	x	sc	227	466	199	665	41730	48616	32613
	1983	-	20	-	x	-	x	x	sc	216	481	124	605	47463	51557	20615
	1987	-	14	-	x	-	x	x	sc	149	355	283	638	37137	45371	16470
	2003	2011	75	x	x	-	-	-	st	897	999	207	1206	56609	64593	103797
	2006	-	81	-	x	-	-	-	st	1273	1408	408	1816	158347	189749	127518
	2007	-	18	-	x	x	x	x	sc	317	533	476	1009	56202	69996	20507
	2008	-	64	-	x	-	-	-	st	1665	1755	944	2699	211416	246073	105550
	2011	-	34	-	x	-	-	-	st	569	963	41	1004	61836	63784	49177

[a] "x" if building or building part is on farm

3.2.3 Embodied Energy in buildings and operational energy

3.2.3.1 Method to estimate embodied energy in agricultural buildings in use

In this study a ‘bottom up’ approach was used to estimate the total material mass input (Gustavsson et al., 2010) and calculate the embodied energy as the cumulative energy demand (Hischier et al., 2010), of the base building materials of the building envelope of agricultural buildings on dairy farms.

Site visits at each dairy farm were undertaken October to December 2011 and detailed investigations made of the farm buildings and their use. Only barns and machinery buildings in full or part use were included. For barns in use for dairy production, all main building elements were included. For example, if a silage tower was part of the barn where the cows were placed, it was included in the calculations, even though it may not have been in use within the period of the data collection.

Where available, building site plans and architectural drawings were used to collate measurements. Additional measurements were made on site, to get basic information of the buildings, such as placement, dimensions, material used for floors, walls, roofs and structural elements and the use of insulation. Also the numbers of places for cows, volume of storage space for manure and fodder were registered. This information was complemented by digital maps and site photos.

Whilst the construction methods and materials used were very similar, the design and detailed layout varied between farm buildings. An analysis of the components found in the envelope of a building and the materials used in constructions revealed that that the use of materials in ground-floor, outer walls, floors and roofs were generally similar and could be categorized. Thus, it was possible to define different sets of building constructions for the farms visited and to calculate the amount of embodied energy per square meter. This method is discussed by Erlandsson and Borg (2003) and used in the same manner or comparable by others (Adalberth, 1997; Dimoudi and Tompa, 2008; Hubermann and Pearlmutter, 2008; Kellenberger and Althaus, 2009; Kohler, 1994; Yohanis and Norton, 2002).

To conduct a ‘bottom up’ approach, the building constructions were analysed for the different layers and types of material they consisted of, including the most important substances (Malmqvist et al., 2011). Based on the type of each material and its density, the mass of each material per square meter was calculated. The mass of each material was then multiplied with the corresponding amount of embodied energy for European conditions accessed from the ecoinvent database (Frischknecht and Rebitzer, 2005). The amount of embodied energy needed per square meter includes production, replacement and dismantling. The sum of the embodied energy of all layers in a square meter of building were aggregated and presented as the amount of embodied energy per square meter in Mega joule (MJ). Steel and timber frames were calculated separately by volume and weight. Based on the analysed buildings we adopted 50 years as a reasonable lifetime estimate. A 50 year service life may be an overestimate for newer buildings (Gustavsson et al., 2010), but is in line with an often used assumption in research papers in the field of LCA (Dux et al., 2009; Stephan et al., 2011). The values used for calculation of a yearly standardized amount of embodied energy are presented in Table 3.3.

Table 3.4 Constructions found in the shell and frame in agricultural buildings and amount of embodied energy.

Building constructions	Main material	Other layers	Insulation	Cladding	thickness	Embodied energy 50 years servicelife
					cm	MJ/m^2
Ground floors	Reinforced concrete slab	Shingle, Lean concrete	no	no	21.0	1132
Intermediate Floors	Reinforced concrete		no	no	27.0	894
	Timber	heavy construction	Rockwool	no	33.0	521
	Timber		Rockwool	no	28.0	370
	Timber	heavy construction	no	no	31.0	255
	Timber		no	no	18.0	105
Walls	Reinforced concrete (basement)	Bitumen waterproofing membrane	no	no	40.0	1385
	Exposed concrete wall		Rockwool	Finery	34.0	1476
	Exposed concrete wall		no	no	15.0	808
	Timber	Solid softwood, polyethylen (PE) vapor barrier, OSB panel, wooden beams, softboard, wood lath	Rockwool	Timber	27.0	770
	Timber	wooden beams, wood lath, solid softwood	no	Timber	24.0	153
	Timber	Solid softwood, polyethylen (PE) vapor barrier, OSB panel, wooden beams, softboard, wood lath	Rockwool	Aluminiumplates	27.0	903
	Timber	wooden beams, wood lath	no	Aluminiumplates	24.0	286
	Steel cassette	Galvanized steelprofiles, polyethylen (PE) vapor barrier, wood lath	Rockwool	Galvanized steelplates	26.0	1543
	Sandwichpanelling	Galvanized steelprofiles	Polyurethane	Steelplates and galvanized steelplates	12.0	1134
Roof framing	Timberjoist				22.0	114
Roofing material	Aluminium trapezoidal sheet				0.2	173
	Asbestos cement				0.7	294
	Roofing felt				0.4	168
	Double walled roof	Solid softwood, polyethylen (PE) vapor barrier, OSB panel, wooden beams, softboard, wood lath			26.0	1424
	Sandwichpanelling	Galvanized steelprofiles	Polyurethane	Steelplates and galvanized steelplates	12.0	1069
						MJ/kg
Frames	Steelframe					18.43
	Timberframe	frequently used dimensions: 18 x 10.5 cm and 18 x 7 cm				4.34

From the ecoinvent database we used the European values of embodied energy as a basis. The available Norwegian values for concrete, timber, aluminium, PVC, insulation materials from rock and roofing materials (Fossdal, 1995; Norwegian EPD, 2014) were used (Table 3.5). Thus, for those materials that most influenced the amount of embodied energy in the building constructions due to their weight and amount of embodied energy, national data was able to be used as mentioned by Malmqvist et al. (2011).

Table 3.5 Construction materials with Norwegian values for embodied energy per kilogram.

Material	Embodied energy MJ/kg	Source
Concrete	0.77	Norwegian EPD, 2014
Timber, construction	4.34	Norwegian EPD, 2014
Timber, cladding	4.06	Norwegian EPD, 2014
Aluminium plates	106.50	Fossdal, 1995
Steel, based on ore	12.24	Norwegian EPD, 2014
Rockwool	11.30	Norwegian EPD, 2014
PVC	56.13	Fossdal, 1995
Chipboard	7.23	Fossdal, 1995
Hardboard	13.93	Fossdal, 1995

Since most of the barns have been extended to adapt to new needs and regulations, we included also extensions as suggested by Erlandsson and Borg (2003). All new and old parts of the barns were included regardless of if they still are in use. For example, all barns built before the year 2000 had silage tower or bunker, but many farmers are now preparing round-balls for storing outside the barn. Finally, disposal of construction waste (Nemecek and Kägi, 2007) and energy needed for building and demolition is expected to be comparable to the 1% found for residential dwellings (Ramesh et al., 2010), and are therefore not accounted for.

The amount of embodied energy in MJ was multiplied with the amount of square meters for each building element. Then the values of all building elements were added together to derive a total value.

The amount of embodied energy (EE) in the shell of a building for the entire lifetime of 50 years was calculated as (see Table 3.6 for abbreviations):

$$EE = EE_{gf} + EE_{mf} + EE_{w} + EE_{r} + EE_{f} \tag{3.1}$$

Table 3.6 Variables and units used in equations and models.

Variable	Unit	Description
AB		All buildings
B		Barn
BT		Barn type. 1 denotes tied barn and 0 denotes loose house barn
BW_cB	m^2	Barn-walls in concrete in barn per cow-place
$BW_{cn}B$	m^2	Barn-walls in concrete or new materials in barn per cow-place
EE	MJ	Embodied energy in base building materials of the building envelope
EE_{gf}	MJ	Embodied energy in ground floors
EE_{mf}	MJ	Embodied energy in intermediate floors
EE_w	MJ	Embodied energy in walls
EE_r	MJ	Embodied energy in roofs
EE_f	MJ	Embodied energy in frame
EE_{pa}	$MJ\ Y^{-1}$	Embodied energy in base building materials of the building envelope per annum
EE_{pacp}	$MJ\ Y^{-1}$ cow-place^{-1}	Embodied energy in base building materials of the building envelope per annum and cow-place
GF	m^2	Square meter ground-floor per cow-place
W_c	m^2	Square meter wall in concrete per cow-place
W_{cn}	m^2	Square meter wall in concrete with insulation per cow-place
OE_{pacp}	$MJ\ Y^{-1}$ cow-place^{-1}	Use of electricity as operational energy on farm per annum
MaM	$MJ\ Y^{-1}$	Net sale of milk and meat from farm per year as nutritional energy
ECM	MJ	Energy corrected milk
GFB	m^2	Ground-floor in barn per cow-place
GFW		Ground-floor walls. 1 denotes ground floor walls are of concrete, 0 denotes timber
IBW		Insulated barn-walls. 1 denotes insulation in barn-walls for dairy cows and 0 denotes no insulation
ST		Silage-store as tower or horizontal bunker. 1 denotes silage-tower or bunker as part of the barn and 0 denotes not
MP		Mode of production. 1 denotes organic production and 0 denotes conventional production
W_cB	m^2	Walls in all buildings in concrete per cow-place
$W_{cn}B$	m^2	Walls in all buildings in concrete or new materials per cow-place

For materials with a shorter lifetime than the expected service life of 50 years, replacement was included. When a part of a building was older than 50 years, we divided the amount of embodied energy of this part by the actual age of this part of the building in 2012. Embodied energy in re-used stones from prior buildings on the farm was not included in the calculation.

The amount of embodied energy in the base building materials of the building envelope per annum (EE_{pa}) for a building was calculated as and measured in MJ per annum as:

$$EE_{pa} = EE\ 50^{-1} \tag{3.2}$$

3.2.3.2 *Variables influencing the amount of embodied energy in barns*

Based on the literature on embodied energy in barns presented in Table 1 and the barns analysed in our study, different variables were tested using multi-linear regression analysis. Continuous variables were the square meter measurements of the ground-floor and walls, and cow-places. In addition we tested dummy variables (see Table 3.4) for use of concrete in ground-floor walls (GFW), insulation in barn walls (IBW), silage store as tower or horizontal bunker (ST), mode of production (MP) and barn type (BT). Prior to the regression analysis the influence of each variable on the amount of calculated embodied energy was tested through linear regression, and only significant variables were included in the final multi-linear regression. When more variables where included, correlations were also tested. Steel cassettes and sandwich panelling were only used on one farm each. Due to the comparable amount of embodied energy per square meter of exposed concrete walls with insulation, they were included in the regressions in the group 'exposed concrete walls'.

The final model for embodied energy in the base building materials of the building envelope in the barn ($EE_{pacp}B$) on farm *i* per cow-place per annum was (see table 3.6):

$$EE_{pacp}B_i = \beta_0 + \beta_1\,(GFB)_I + \beta_2\,(BW_cB)_i + \beta_3\,(BW_{cn}B)_i + \varepsilon_i \tag{3.3}$$

3.2.3.3 *Barn and other buildings in use*

Many of the barns were not only used as barns, with some also including silage towers, hay store and machinery storage. Additional buildings are also frequently in use for machinery storage and older barn buildings may still be utilized for heifers and calves. To analyse the effect of extra buildings in addition to the main barn, the sum of embodied energy of the barn and other agricultural buildings in use were also tested. We used the same approach as for the barn (see equation 3.3) and analysed the same variables. The different variables were tested using multi-linear regression analysis with regard to the annual embodied energy in the envelope of both the barn and the other buildings in use per cow-place.

The result for our final model for embodied energy in the base building materials of the building envelope in all buildings ($EE_{pacp}AB$) on farm *i* per cow-place per annum was:

$$EE_{pacp}AB_i = \beta_0 + \beta_1 (GFB)_i + \beta_2 (W_cB)_i + \beta_3 (W_{cn}B)_i + \varepsilon_i \qquad (3.4)$$

3.2.3.4 *Operational energy in housing*

In Norway, electricity on a dairy farm is the main source for operational energy in barns and is used for light, ventilation, warming of water and heating the milking parlour for loose housing, cooling of milk, milking and feeding. Electricity is also used in other agricultural buildings, thus the measured amount of used electricity includes the use for the entire dairy farm. Tractors used to transport round-balls into the barn or to take out solid manure are not included in the calculations.

Norway is nearly self-sufficient in hydropower electricity; therefore the amount of primary energy per kWh is low compared to many other European countries where coal or natural gas is used for electricity production (Dones et al., 2007). In table 3.5 the energy needed to produce 1 kWh of high voltage electricity at grid for those countries is listed, where literature on embodied energy in agricultural buildings are referred to in this article.

Table 3.7 Energy use in MJ from different sources for1 KWh high voltage electricity at the grid in different countries in Europe.

	CH	DE	DK	FR	GB	NL	NO	SE
Biomass	0.06	0.16	0.86	0.05	0.22	0.34	0.16	0.94
Non-renewable fossil	1.59	7.36	7.20	1.05	7.72	9.50	0.39	0.95
Nuclear	6.86	3.48	0.83	10.60	2.79	1.18	0.60	6.00
Forest	8.73E-07	1.74E-06	3.01E-06	7.08E-07	2.75E-06	2.94E-06	2.57E-07	5.45E-07
Solar	1.16E-03	3.55E-03	2.93E-04	2.01E-05	1.80E-05	5.78E-04	3.74E-06	3.96E-05
Water	1.26	0.20	0.27	0.44	0.07	0.04	3.47	1.48
Wind	0.02	0.17	0.56	0.01	0.02	0.09	0.03	0.03
Sum all	9.78	11.37	9.73	12.15	10.82	11.15	4.65	9.41
% non-renewable	86 %	95 %	83 %	96 %	97 %	96 %	21 %	74 %

Source: ecoinvent V2.2 (2010)

The average use of electricity for 2010 and 2011 for conventional farms in the participating Norwegian farms was 172,000 MJ, and for organic farms 182,000 MJ. For each farm the amount was multiplied with the value of primary energy from the ecoinvent database V2.2 2010 (Frischknecht and Rebitzer, 2005) for the electricity mix in Norway (4.65 MJ per KWh) to get the annual amount of primary energy linked to operational energy used per dairy farm.

As for the embodied energy in barns and all buildings, all registered variables were tested (see equation 3.1) using multi-linear regression analysis with regard to their influence on electricity use.

The result for the final model for electricity as operational energy (OE) on farm *i* per annum was:

$$OE_{pai} = \beta_0 + \beta_1 (MaM)_i + \varepsilon_i \qquad (3.5)$$

3.2.4 Functional units

3.2.4.1 Dairy cow-places and area

The number of dairy cow-places is the number of bedding places in the barn for dairy cows.

Barn area per cow-place is measured in square meters and calculated by ground floor area for the entire barn (see Fig. 3.1) and divided by number of places for dairy cows in the barn. When a slurry tank is placed outside the barn the basal area of the tank is not added to the ground floor area of the barn, to get a comparable approach to the barns where the slurry is stored in the cellar.

The area of all buildings per cow-place is measured as the sum of square meters ground floor of barn and machinery building(s) divided by number of dairy cow-places.

3.2.4.2 Energy corrected milk and nutritional energy in milk and meat

Milk includes both fat and protein in differing amounts. To compare milk on the basis of the energy content, the amount of milk mass can be standardized to a kg of energy corrected milk (ECM) (Sjaunja et al., 1991; Yan et al., 2011):

$$1\ \text{kg ECM} = 1\ \text{kg milk}\ (0.250 + 0.122\ \text{fat}\ \% + 0.077\ \text{protein}\ \%) \tag{3.6}$$

Norwegian milk is sold with 3.9 % fat and 3.3 % protein (Norwegian Food Safety Authority, 2015). Using the formula for ECM, 1 kg milk has a nutritional energy content of 2.85 MJ. For 1 kg per carcass of cow, the content of nutritional energy is assumed as 6.47 MJ per kg, for the carcass of a calf, the value is 5.82 MJ per kg (Heseker and Heseker, 2013; Kraatz, 2009).

For animals sold as live-animals, we estimated the carcass weight based on the average dressing percentage for a Norwegian Red, 52.5 percent (Tine, 2014). The weight of live animals bought were subtracted from the live weight of animals sold to calculate the net production on the farm (Bleken et al., 2005).

3.2.4.3 Co-products and other animal products

The farmers sold milk, meat and surplus calves. The ways of handling these co-products have an impact on the results (Cederberg and Stadig, 2003; Kraatz, 2009). Based on ISO 14044 (ISO, 2006), where physical properties are mentioned as first choice, we sum up the production of milk, meat and sold animals in calorific values for human nutrition. Although the farms were mainly dairy farms, some had some sheep. Net sheep meat productions on five of the dairy farms were estimated (between 0.1 and 0.7 percent of overall farm net nutritional production) and also included.

3.3 Results

3.3.1 Energy embodied in the envelope of barns

On average for the 20 barns, the value of embodied energy in the envelope of barns per cow-place and year was about 2,140 MJ (Fig. 3.2). The variation in amount of embodied energy per cow-place was higher for the farms built after 2000 than for those built earlier.

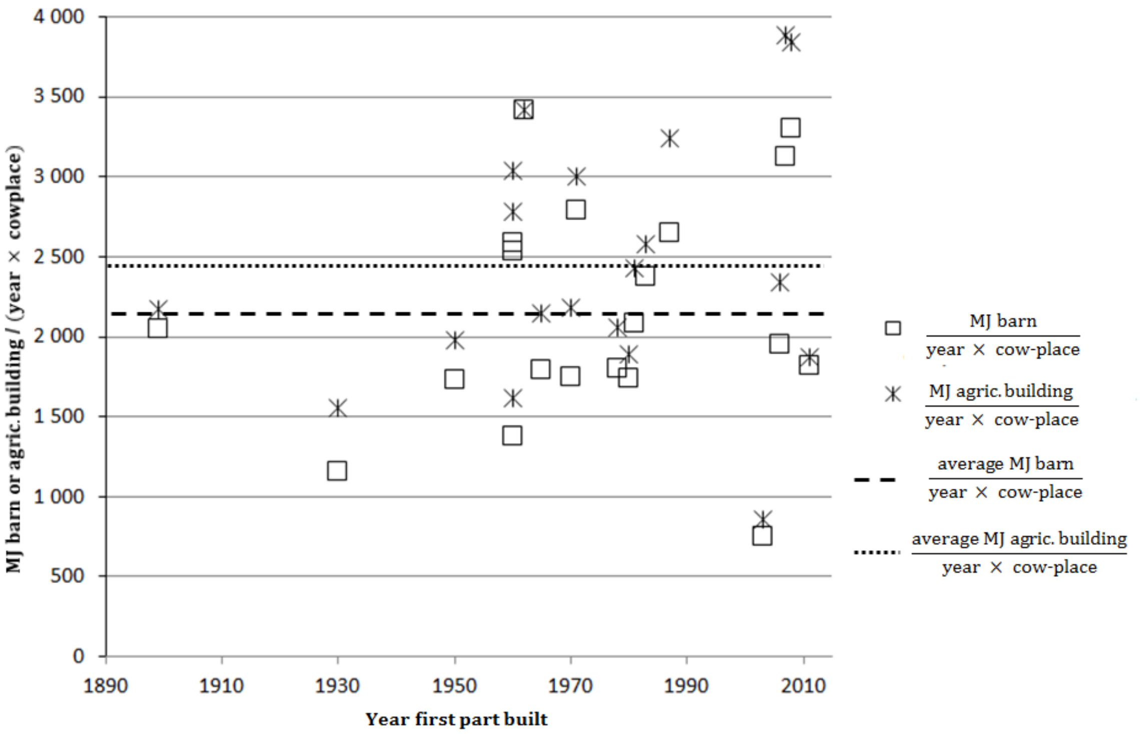

Fig. 3.2 The amount of embodied energy in the envelope of barns and all agricultural buildings per cow-place in relation to the year the first part of the barn was built.

The barns built after the year 2000 were all built as free-stall barns. The value for the barn built in 2007 is 755 MJ per cow-place and year and the lowest of all barns. Using nearly only timber in walls and only insulating service rooms in combination with reduced use of concrete are reasons for the low value. Machinery on the dairy farms is used for producing fodder on the farm. Thus the embodied energy in buildings for machinery should be included, when the embodied energy on dairy farms is estimated. Walls and roof framing of buildings for machinery are often in timber and old barns are often reused for machinery. Due to these factors, the amount of embodied energy in machinery buildings is relatively low compared to barns and they contribute on average only 12 % to the overall amount of embodied energy on dairy farms (see Fig. 3.2 and Table 3.8).

The values from Fig. 3.2 are split up in Table 3.8 for the amount of embodied energy per cow-place and year in floors, walls and roofs for barns and other agricultural buildings. On average floors and walls contribute about 40 % each, while roofs contribute nearly 20 %. The highest amount of embodied energy in the roof is found for the barn built in 2008. The reason for this high value is that sandwich panelling was used as a roofing material and thus the embodied energy for insulation is part of the roof.

Table 3.8 The amount of embodied energy per cow-place and year in different building components of agricultural buildings on dairy farms.

	Barns				Other agricultural buildings				All agricultural buildings
Year[b]	Floors[a]	Walls[a]	Roofs[a]	Sum[a]	Floors[a]	Walls[a]	Roofs[a]	Sum[a]	Sum[a]
1899	1 047	697	352	2 096	42	23	16	81	2 177
1930	698	343	127	1 169	239	56	88	383	1 552
1950	910	536	295	1 741	107	78	55	239	1 980
1960	1 190	1 101	246	2 537	140	66	39	245	2 782
1960	584	567	227	1 379	157	33	52	242	1 621
1960	1 086	1 089	409	2 585	270	80	100	450	3 035
1962	1 358	1 764	293	3 414	0	0	0	0	3 414
1965	650	891	249	1 790	311	39	4	354	2 144
1970	651	737	357	1 745	239	76	121	436	2 181
1971	1 397	1 006	395	2 798	95	27	86	208	3 006
1978	818	613	367	1 797	149	71	44	263	2 061
1980	1 001	560	182	1 744	103	10	30	143	1 886
1981	894	847	345	2 087	226	53	65	344	2 431
1983	850	1 317	205	2 373	140	25	40	205	2 578
1987	889	1 565	199	2 653	457	39	92	588	3 241
2003	335	184	236	755	63	11	33	106	861
2006	793	560	601	1 955	224	68	95	388	2 343
2007	1 080	1 538	503	3 122	495	128	144	766	3 889
2008	1 040	626	1 637	3 303	258	133	151	542	3 845
2011	993	536	289	1 819	0	11	46	57	1 876
average all farms	913	854	376	2 143	186	51	65	302	2 445
percent of building	43 %	40 %	18 %	100 %	61 %	17 %	22 %	100 %	
percent of all buildings	37 %	35 %	15 %	88 %	8 %	2 %	3 %	12 %	100 %

[a] MJ cow-place^{-1} year^{-1}

[b] The year is the year when the oldest part of the barn was built at this farm

Square meter area per cow-place in the barn, use of concrete in walls and insulation in walls of concrete (including steel cassettes and sandwich panelling) all increase the amount of embodied energy (Table 3.9). The mode of production (organic or conventional), the age of the building, number of cow-places, and inclusion of silage towers or hay stores had no significant effect and were not included in the final regression.

Table 3.9 Variables, influencing the amount of embodied energy in barns.

Coefficients[a]	Estimate	Std. Error	P-value
(Intercept)	234.5	231.9	
Square meter ground-floor in all barns per cow-place	60.1	11.3	< 0.001
Square meter walls in all barns per cow-place	37.6	8.0	< 0.001
Square meter concrete walls with insulation or barn-walls in new materials in all barns per cow-place	26.1	11.0	0.01

R^2: 0.897
[a]Equation 3.3

3.3.2 Energy embodied in all agricultural buildings

Other buildings contribute little to the overall amount of embodied energy. Square meters ground-floor in all buildings and insulated concrete in walls (including steel cassettes and sandwich panelling) per cow-place are the two most significant contributors to the amount of embodied energy in the envelope of all buildings and explain more than 90 % of the total variation (Table 3.10).

Table 3.10 Variables, influencing the amount of embodied energy in all buildings on dairy farms.

Coefficients[a]	Estimate	Std. Error	*P*-value
(Intercept)	178.5	247.5	
Square meter ground-floor in all buildings per cow-place	59.8	9.6	< 0.001
Square meter concrete walls in all buildings per cow-place	14.8	10.7	
Square meter concrete walls with insulation or barn-walls in new materials in all buildings per cow-place	36.2	9.8	0.001

R^2: 0.907
[a]Equation 3.4

3.3.3 Embodied energy in relation to actual production

For both organic and conventional farming there is a large variation in the annual amount of embodied energy per cow-place (Fig. 3.3). In addition, the amount of embodied energy in the barns was related to the combined amount of nutritional energy in net milk and meat sold, where all net sold animals were calculated as meat production. Since organic farms on average have cows with lower milking yield, the amount of embodied energy from the barns per MJ nutritional energy in sold milk and meat ($EE_{pa}B$ MaM^{-1}) is on average higher (0.187) than for conventional farms (0.122). In relation to the overall energy use from cradle to farm gate, barns accounted for 10 % on conventional and 17 % on organic farms due to a higher energy use on conventional farms. The share of barns to the overall energy use varied from 5 to 30 %.

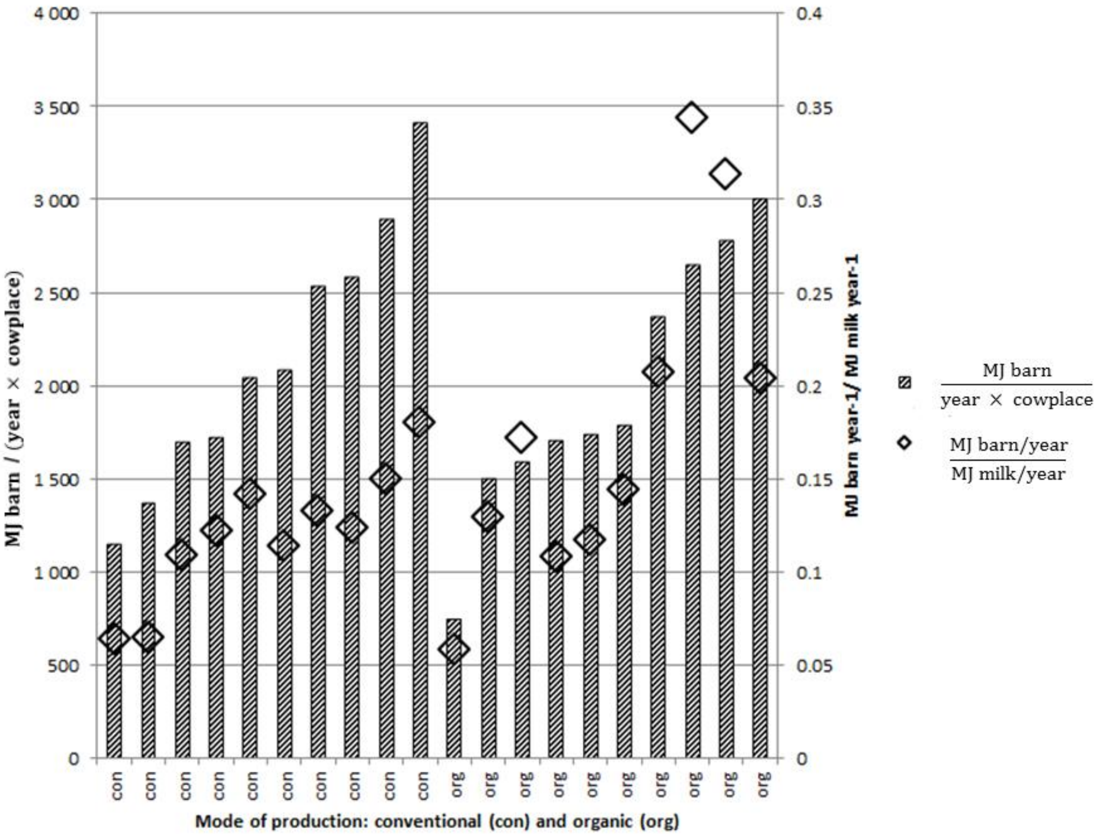

Fig. 3.3 The annual amount of embodied energy in barns per cow-place and relation of annual amount of embodied energy in barns to annual nutritional energy in sold milk and meat on conventional and organic dairy farms.

3.3.4 Variables influencing the amount of electricity consumed per cow-place and year

In our study, the use of electricity per annum varied from 3,000 to 10,000 MJ primary energy per cow-place needed to produce and distribute the electricity used on farm (average of 8,900 MJ). This comprises between 0.67 and 1.87 MJ of primary energy per kg ECM (average 1.22 MJ per kg ECM).

More electricity was used when more milk and meat (higher production of nutritional energy) was produced or there were additional buildings for young cattle. Extra buildings for machinery decreased the use of electricity. The R^2-value of 0.63, the explanation of primary energy needed for electricity consumed per cow-place was low (see Table 3.11), and thus there are expected to be additional variables influencing the electricity consume which were not included in this study.

Table 3.11 Variables, influencing the amount of electricity used on dairy farms.

Coefficients[a]	Estimate	Std. Error	*P*-value
(Intercept)	5532.4	1739.3	
Net sale of milk and meat from farm per year as nutritional energy	0.2	0.0	0.001
Extra building for young cattle	2340.5	719.1	0.001
Extra building for machinery	-2655.8	1215.6	0.01

R^2: 0.634

[a] Equation 3.5

Summing up embodied energy in the envelope of the barn per annum, technical equipment, rubber mattresses (Kraatz, 2009) and primary energy to produce the electricity used per year, the share of primary energy to produce the electricity varied from 56 % to 84 %, with an average of 70 %.

3.4 Discussion

For barns and other agricultural buildings on dairy farms, we found large differences in the amount of embodied energy in the building envelopes. The differences were mainly due to square meter area and the different amounts of base building materials used. Our findings for barns and milk production (on average 2,140 MJ per cow-place and 0.43 MJ per litre of milk) were in the range of results found in other publications (see Table 3.1) where the amount of embodied energy was included, measured on the basis of embodied energy in barns in MJ per cow (740-5,800 MJ) and litre of milk (0.09-1.26 MJ).

We found a high variation for the amount of embodied energy in the building envelopes. This is in contrast to the assumption that buildings are generally similar and thus no significant differences are expected (Dalgaard et al., 2001; Dux et al., 2009). It is not surprising that square meter area per cow-place was found to be an important factor for the amount of embodied energy. This underlines that the values for embodied energy for housing per cow in ecoinvent should only be used when buildings analysed are comparable to those used to calculate the ecoinvent data. Lebacq et al. (2013) find that in herbivore livestock farming, 20 % of the energy used relates to machinery and buildings and write that farmers have little leeway to change this consumption. In contrast to this, we conclude for the barns investigated in this study, that by choosing materials with a low amount of embodied energy and a design that requires less material consumption as well as increasing the lifetime of a building, the farmer can significantly reduce the annual amount of embodied energy in buildings.

The type of building materials used is an important variable in the amount of embodied energy calculated for the analysed barns. This finding is in line with Buchanan and Honey (1994), who concluded that wood constructions have less embodied energy than concrete and steel structures in a detailed study of office and residential buildings in New Zealand. It is not surprising that in this study the results for older dairy barns were lower per cow-place than the values found in the ecoinvent database as, except the cellar, mainly wood were used in walls and the construction. Due to the use of materials with a higher amount of embodied energy such as concrete and steel structures in newer buildings, we found higher amounts of embodied energy in the building envelopes, comparable to the values in the ecoinvent database. Ecoinvent has one value for tied and one for loose house barns. This is in contrast to our findings which did not indicate that the type of housing influenced the amount of embodied energy per cow-place.

The data was thoroughly collected, but the use of estimates may lead to minor errors. Errors can occur in the collection of data and be part of the values for embodied energy used. Both can lead to over and underestimations in the results (Gustavsson et al., 2010). Since the results found are significant, minor errors from data collection are not expected to change the results (with exception for primary energy needed for the production on electricity used). Where possible, Norwegian values were used for embodied energy. When Norwegian values were not available ecoinvent values for embodied energy in Europe were applied. However it is recognized that these values will not be representative for all Norwegian or local situations.

The approach used in this study can assist in the inclusion of the embodied energy of buildings as an integral part of long term agricultural systems design and management. It is easily adapted and transferred to other conditions and countries. The present study was conducted in the coastal area northwest of Norway. The finding of variables influencing the amount of embodied energy appears to be representative for dairy farming in other Norwegian regions and with comparable use of building materials. The presented method can easily be adapted to other materials used and local values for embodied energy.

Both existing and planned buildings can be analysed using this approach. Essentially, the amount of embodied energy for each material can be found in existing databases, but local or regional data can be difficult to find. The effect of combining data from different databases should be carefully considered. By summing up the amount of building construction materials, comparisons can be made for different existing or planned solutions. One possibility to further integrate embodied energy into planning is to introduce computer aided drafting software, as done by the Bauteilekatalog in Switzerland (Paolantonio, 2007). In this solution, the embodied energy is linked to the planned constructions and calculated while a building is planned. When including embodied energy considerations into building construction planning, the overall costs to the farmer should be considered (Pannell, 2001).

For a farmer interested in sustainable production it is important to know the amount of embodied energy of existing and planned buildings to see how big the impact in regard to the overall energy consumption is. This is one step to assessing how environmentally friendly production on the farm is, can help to communicate this to consumers and to find strategies to improve production.

An important part of the work was to find the amount of embodied energy for each material and to calculate the amount of embodied energy for the different building constructions in use. Analysing more barns would not increase this part of the work, unless additional building constructions were involved, and thus the workload per barn could be reduced. A site visit and detailed investigation of the farm buildings and their use will always be necessary.

Based on the results from the regression analysis on variables influencing the amount of embodied energy in a barn per cow-place (equation 3), the five groups of approaches presented in section 1 differ in their ability to describe the amount of embodied energy for the buildings analysed:

1) The mass material calculation would be suitable to reflect different use of materials and design of buildings.
2) The approach of different building constructions was used in this study and functioned well (reflected as high R^2-values).
3) Square meter ground floor per cow-place in the barn was a significant contributor (R^2-value of 0.90).
4) Embodied energy per cow increased by square meter ground floor in the barn, the volume of concrete in walls, as well as insulated concrete walls (including steel cassettes and sandwich panelling). A fixed amount per cow would underestimate this effect.
5) A fixed combination of materials for all buildings would not fit well to buildings in this study. Different building materials as well as use of insulation significantly influenced the results.

As mentioned by Roer et al. (2013), the small barn structure in Norway and a long indoor housing and feeding season, leads to high investments in buildings compared to other countries. The amount of embodied energy in dairy buildings in Norway is comparable to high values also found in Switzerland. Nemecek and Kägi (2007) note that “agricultural farm buildings in Switzerland are of expensive, solid construction”. The published values for tied and loose house barns found in the literature (see Table 1) include also technical equipment and not only the envelope. To compare the results from our study, about 475 MJ per cow-place and year (Kraatz, 2009) must be added for Norwegian conditions, where rubber mattresses are used.

The lifetime of the building has an important influence on the estimated annual amount of embodied energy; however this is rarely discussed in the literature for agricultural buildings. A longer actual lifetime reduces the annual contributions. As shown by the age of some of the barns in this study, the lifetime of the envelope of building-parts can reach more than 100 years, when it is maintained. Increasing the lifetime of a building is a possibility for the farmer, to reduce the annual amount of embodied energy. However, buildings can become technically outdated and thus the technical lifetime can be shorter than the building lifetime. A technical lifetime of 20 years (Dalgaard et al., 2001; Nielsen and Rasmussen, 1977) will result in higher annual values for embodied energy than a lifetime of 80 years (Williams et al., 2006). For the new buildings in our project a technical lifetime of 20 years would increase the amount of annual embodied energy by a factor of approximately 2.5.

In our study the yearly use of operational energy for the dairy farms corresponds to 70 % (range 56–- 84 %) of the sum of embodied energy in the envelope of the barn per annum and operational energy. This underlines the importance of operational energy and the variation between farms indicate that for some of the farms it should be possible to reduce the use of electricity. The share found is lower than the 80-90 % found by Ramesh et al. (2010) in their review of the level of operational energy used for residential and office buildings across 13 countries. A reason for this difference may be that only parts of a barn are heated, compared to residential and office buildings. The amount of electricity used per kg ECM on the farms was higher than reported by Dalgaard et al. (2001), Refsgaard et al. (1998) and Roer et al. (2012). A possible reason for the high registered electricity consumption despite a low amount of embodied energy may be the inclusion of electricity use for other farm buildings and other farm purposes. Unlike many other countries, electricity on dairy farms in Norway usually is used for heating some rooms and warm water, to cool milk and, if necessary, to defrost frozen silage in wintertime. These activities increase the consumption of electricity.

When comparing electricity use, it is important to know, if the electricity consumed on the farm or the embodied energy needed to produce the consumed electricity is reported in publications. Often this is not mentioned. To produce the energy-mix for electricity in for example Norway, Denmark and Germany, an energy amount of 4.7, 9.7 and 11.4 MJ per kWh is needed (see Table 7). If only non-renewable sources are included (as done for example by Kraatz (2012)), the numbers are 1.0, 8.0 and 10.8 (see table 3.5). Irrespective of whether all energy sources or only non-renewable sources are included, in Norway the amount of embodied energy for the production of 1 kWh electricity is less than half of that of other European countries due to a more environmentally friendly production of electricity, mainly based on hydropower. Despite the area of the ground-floor being an important variable in influencing the amount of embodied energy, planning a new barn should also take into account working conditions within the buildings, demand little ongoing operational energy, provide desirable animal welfare conditions and be cost effective. Also the requirement for more area per animal within organic production demands more ground floor area. Combined with lower milking yield found on average for organic farms, it is especially important for organic farmers to take into account the effect of chosen building material and design of the building envelope on embodied energy.

3.5 Conclusion

The bottom-up approach (Adalberth, 1997; Kohler, 1994) was useful to calculate the amount of embodied energy per square meter in the envelope of buildings on dairy farms. The approach can easily be transferred and used for other buildings as well as in other countries. It allows users to estimate the amount of embodied energy in the envelope of existing buildings and to calculate the effect of using different construction materials and methods on the amount of embodied energy in planned buildings. Thus it is useful in making recommendations on how to construct new buildings using less embodied energy in the envelope, and to communicate how the choice of materials influences the amount of embodied energy in buildings.

The amount of embodied energy in the envelope of the barns analysed varied from about 750 to 3,410, with an average of 2,140 MJ per cow-place and year, and varied from 0.06 and 0.34 MJ per MJ nutritional energy in milk and meat sold (average 0.15 MJ per MJ nutritional energy in milk and meat sold).

Variables leading to a higher amount of embodied energy in the envelope of barns were in decreasing order of importance: area per cow-place in the barn, area of concrete walls and area of insulated concrete walls (including steel cassettes and sandwich panelling).

For all agricultural buildings in use, square meter area per cow-place in all buildings and square metre of insulated concrete walls (including steel cassettes and sandwich panelling) were the values leading to a higher amount of embodied energy in the buildings envelope.

More electricity (operational energy) was used when milk yield increased and more meat was produced per cow or there were additional buildings for young cattle on a farm, while extra buildings for machinery decreased the use of electricity. But the variables found had a low explanation of the overall use of operational energy and thus there are expected to be additional variables influencing the electricity consume which were not included in this study.

3.6 Acknowledgements

Funding from the Norwegian Research Council (grant number 199487/E40) and ‘Møre og Romsdal’ County Municipality, Division for Agriculture and Food are gratefully acknowledged. We would like to thank the participating farmers for their interest and willingness to collect data with us and share needed information. The authors are grateful to Andrew Pope and the two reviewers for helpful comments and suggestions to improve the article.

4 Variation in energy utilization in dairy farming on conventional and organic Norwegian dairy farms and possibilities for improvement

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4.a Abstract

Due to the limited resources of fossil fuels and the need to mitigate climate change, the energy utilization for all human activity has to be improved. The objective of this study was to analyse the correlation between energy intensity on dairy farms and production mode, the influence of machinery and buildings on energy intensity and to find production related solutions for conventional and organic dairy farms to reduce energy intensity. Data from ten conventional and ten organic commercial dairy farms in Norway from 2010-12 were used to calculate the amount of embodied energy, which was calculated as the sum of primary energy used for production of inputs from cradle to farm gate using a life cycle assessment (LCA) approach. Energy intensities for dairy farms were used to show the amount of embodied energy used by inputs per metabolizable energy in the output. They allow also to easily point out the contribution from different inputs. The organic farms produced on average milk and meat with lower energy intensities than the conventional ones. On conventional farms, the energy intensity calculated on all inputs was 2.6 ± 0.4 and on organic farms it was significantly lower at 2.1 ± 0.3. On conventional farms, machinery and buildings contributed 18 % ± 4 %, on organic farms 29 % ± 4 % to the overall energy use. The high relative contribution of machinery and buildings to the overall energy consumption underlines the importance of considering them when developing solutions to reduce energy consumption in dairy production.

The high variation of energy intensity on all inputs from 1.6 to 3.3 (4.5 to 9.3 MJ kg^{-1} milk) found on the 20 farms shows the potential for producing milk and meat with low energy intensity. Based on the results, separate recommendations were given for conventional and organic farms on how to reduce energy intensity.

4.b Keywords

Efficiency; Life cycle assessment; milk; meat; building; machinery;

4.1 Introduction

Agriculture's green revolution was the main cause for the significant increase in food production that was able to satisfy the food needs for a large share of the growing population. Inputs such as fertilisers, pesticides and farm machinery replaced man- and animal-power and contributed to the production increase. However, this development resulted in a high dependency on external energy. This dependency got its first public attention during the oil crisis of the early 1970s, and Pimentel et al. (1973) published one of the first studies on energy intensity in agriculture. The amount of energy necessary to produce milk on dairy farms has been calculated in many European studies (e.g. Cederberg et al., 2007; Erzinger et al., 2004; Hersener et al., 2011; Rossier and Gaillard, 2004; Thomassen et al., 2008; Upton et al., 2013). Some of the studies include organic and conventional farms (Cederberg and Flysjö, 2004; Thomassen et al., 2008; Werf et al., 2009). Most of the studies do not include energy use linked to machinery, barns and other agricultural buildings (Yan et al., 2011). However, the share of embodied energy in buildings can be substantial and has been reported to be from 17 % (Dux et al., 2009) to 32 % (Rossier and Gaillard, 2004) of the total energy consumption on commercial dairy farms in Switzerland.

In Norway, dairy farming is an important part of agriculture with 31 % of all farms having dairy production in 2015[5]. Due to long winters, the vegetation period is short and animals have to be kept in barns for most of the year. The short vegetation period requests the production and storing of much winter fodder. And barns for long and cold winters in Norway are expected to lead to a high energy input in dairy farming, because of embodied energy for insulation and heating in milking parlours. Despite studies in other Scandinavian countries, energy intensities on commercial conventional and organic dairy farms have not been addressed under Norwegian conditions yet.

The objective of this study on dairy farms was to find out if:

- the energy intensity for producing food differs with production mode,
- embodied energy in machinery and buildings contributes significantly to the farm's total energy intensity,
- different solutions for different modes of production have to be chosen to reduce energy intensities.

In this study we use energy intensities to compare the utilisation of energy on different farms producing milk and meat. Energy intensities (Bullard and Herendeen, 1975) are in this study the amount of primary energy from cradle to farm gate needed to produce one MJ of metabolizable energy in milk and meat. Energy intensities are calculated with the sum of primary energy (from regenerative and fossil resources) of inputs in the nominator and the amount of produced metabolizable energy from milk and meat in the denominator. Intensities make it possible to assess the influence of each input individually, which is not possible with efficiencies. Intensities are the inverse of efficiencies and like them dimensionless.

In literature different energy intensities are used as indicators for the resource use on farms. For grain production, for example, energy consumption per kg grain is used (Hülsbergen et al., 2002) and for dairy production the energy use per kg milk (Kraatz, 2012) is used. Although the same calculation is applied, intensities are also named energy requirement (Uhlin, 1998), energy use (Vigne et al., 2013) or energy cost (Refsgaard et al., 1998).

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[5] https://www.ssb.no/jord-skog-jakt-og-fiskeri/statistikker/stjord (accessed 10.08.2016).

4.2 Material and methods

4.2.1 Farm selection and description

The study was based on farm data from 10 certified organic and 10 conventional commercial dairy farms in the county of Møre og Romsdal in central Norway for the calendar years 2010 to 2012. The selected farms differed in number of dairy cows, milking yield, farm area per cow, fertilisation, and forage to concentrate ratio to reflect variations found in the county.

The county is mainly located in a coastal area around 63°N, where the outdoor grazing period is usually not more than three months for dairy cows. On cultivated area, only grass and grass-clover leys are grown.

4.2.1.1 Farm areas

The Norwegian Agriculture Agency distinguishes between three categories of utilised agricultural area: fully cultivated land, surface cultivated land, and native grassland (Fig. 4.1). To reflect the different levels of possible yields, each hectare of fully cultivated land was multiplied with 1, of surface cultivated land with 0.6 and of native grassland with 0.3. The sum of these areas is referred to as weighted farm area. Free rangeland consists mainly of native woodland or alpine vegetation, and can only be used for grazing. The area of free rangeland is not included in the dairy farm area. The area used to produce fodder or fodder-ingredients for concentrates purchased by the farm is named off-farm area because this area is not owned by the farm itself, but is essential for the farm's dairy production and thus part of the dairy system (DS).

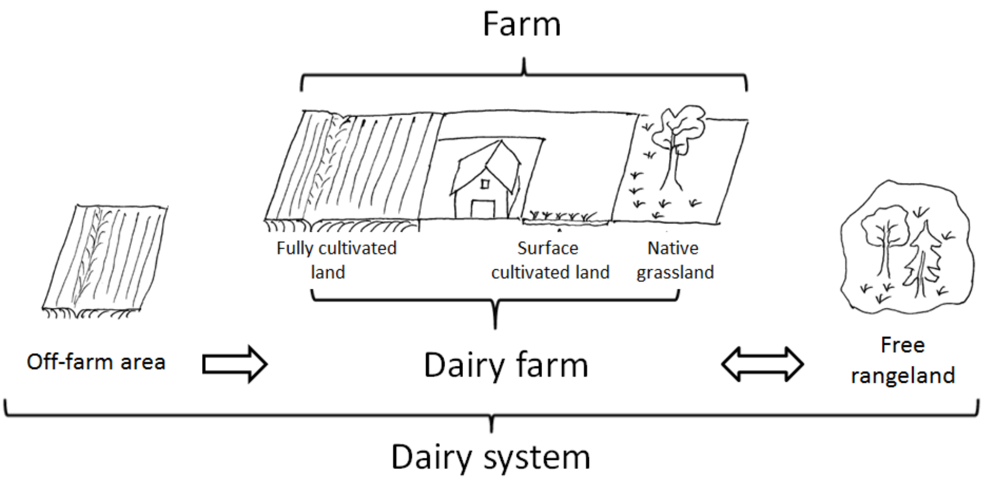


Fig. 4.1 Different categories of areas for the dairy farm and the dairy system.

4.2.1.2 System boundaries

We defined dairy farm area as the area on which purchased inputs are used for dairy cows and other cattle. The system boundaries for the dairy system include dairy farm area and cattle herd, and in addition off-farm area for growing imported roughages and concentrate ingredients. We applied a farm gate trade balance and only farms with dairy production as their main enterprise were selected. When farms had some sheep, horses, or sold silage, area and inputs for non-dairy production were subtracted from weighted farm area and thus excluded from our calculations.

4.2.1.3 Farm data and sources

Data from the 20 farms were collected for the calendar years 2010 to 2012 to calculate average annual values, thus reducing the influence of weather variations. The information collected included farm area, livestock numbers, number of grazing days on different areas, and amount and type of manure applied. Farm visits were used to introduce the data collection forms and prepare farm maps. In addition to costs and income figures, accounting data included quantities and type of product.

The main characteristics of the farms are shown in Table 4.1. Feed demand, grazing uptake, harvest and weight gain are in detail described in chapter 2.2.2.1.

Table 4.1 Main characteristics of the dairy farms.

Parameters	Units[a]	Conventional	standard deviation	Organic	standard deviation
Farms	n	10		10	
Fully cultivated land	ha	26.8	13.6	33.0	23.7
Surface cultivated land	ha	0.3	0.4	0.2	0.5
Native grassland	ha	13.6	22.7	11.3	14.7
Dairy farm area (DF); weighted[c]	ha	31.1	19.6	36.5	26.3
Off-farm area	ha	28.2	16.7	24.9	20.2
Dairy system area (DS)	ha	59.3	34.6	61.4	46.3
Share of energy uptake on free rangeland in relation to entire feed uptake by cattle	%	5.9	3.9	8.1	8.2
Cows per farm	cows farm^{-1}	29.5	16.4	29.4	17.3
DF Stocking rate	cows ha^{-1}	0.9	0.3	0.8	0.2
DS Stocking rate	cows ha^{-1}	0.5	0.1	0.5	0.1
Liveweight cow	kg cow^{-1}	570	40	545	75
Milk delivered per cow[b]	kg ECM cow^{-1} year^{-1}	7 301	582	5 490	1 679
Milk delivered per DF area	kg ECM cow^{-1} year^{-1}	7 206	2 205	4 590	1 097
Milk delivered per DS area	kg ECM cow^{-1} year^{-1}	3 646	594	2 776	514
DF Area per milk delivered	m^{2} kg^{-1} ECM	1.5	0.6	2.3	0.6
DS Area per milk delivered	m^{2} kg^{-1} ECM	2.8	0.6	3.7	0.7
Milk fat	%	4.09	0.25	3.89	0.22
Milk protein	%	3.39	0.08	3.28	0.12
Replacement rate	%	41.4	10.0	33.6	8.0
Diesel use on DF	l ha^{-1} year^{-1}	179	68	96	36
Working hours on farm	h farm^{-1} year^{-1}	4 014	507	3 802	736
Return to labour per recorded working hour	€ h^{-1}	14.7	6.8	14.5	4.5

[a] Units of parameters are given. Numbers for participating farms are means for average of kalender years 2010-12 with standard deviation.

[b] Milk delivered includes milk sold to dairy and private use

[c] Weighted area = Fully cultivated land + 0.6 Surface cultivated land + 0.3 Native grassland

4.2.2 Farm status

4.2.2.1 Embodied energy in purchase and off-farm area

Concentrates purchased by the farmers consist of several ingredients produced in different countries. The use of agricultural area and amount of embodied energy (MJ kg^{-1}) of each ingredient was taken from the MEXALCA report (Nemecek et al., 2011) and the additional energy demand for transportation was calculated using ecoinvent v3.2 (Weidema et al., 2013). For all other purchased products the embodied energy was calculated from the cumulative energy demand from ecoinvent version 3.2, including all non-renewable and renewable energy resources from cradle-to-gate except manpower and solar radiation.

While the embodied energy for the inputs are presented in Table 4.3, free rangeland is an exception. Because no non-renewable and renewable energy was needed for the production of feed, taken in on free rangeland, the presented values, are the calculated metabolic energy in milk and meat gain produced on free rangeland.

4.2.2.2 *Embodied energy in agricultural buildings and machinery*

To calculate the amount of embodied energy in agricultural buildings a ‘bottom up’ approach was used. The approach, data collection, and calculating the amount of embodied energy in the envelope of the buildings is in detail described by Koesling et al. (2015). For embodied energy for technical equipment in the barns, values from Kraatz (2009) were added. For embodied energy in building materials (Table 4.2), we used data from Norwegian Environmental Product Declarations (Norwegian EPD, 2014) and Fossdal (1995).

For each farm, a record of all machinery used in agriculture was prepared, including type of machinery, brand, model, weight, and year of fabrication and purchasing. Machinery was categorized into the groups for agriculture according to ecoinvent V2.2 (Hischier et al., 2010), as they are: agricultural machinery, general or tillage, slurry tanker, trailer and tractor. To calculate the amount of embodied energy per year, the weight for each machine was multiplied with the ecoinvent value and then divided by the expected service life for the corresponding category. For example, for a tractor the service life is expected to be 12 years (Nemecek and Kägi, 2007). The tractor weight was calculated as the weight of all tractors on farm divided by farm area. If a machine was older than the expected service life, we divided the amount of embodied energy by its age in 2012 to get the annual value of embodied energy.

Table 4.2 Construction materials with Norwegian values for embodied energy per kilogram.

Material	Embodied energy ($MJ\ kg^{-1}$)	Source
Aluminium plates	106.5	Fossdal, 1995
Bitumen roof waterproofing, multi-layer	24.4	NEPD 00270E, 2014 [a]
Bitumen waterproofing, multi-layer	24.4	NEPD 00270E, 2014 [a]
Chipboard	12.6	NEPD 00274N, 2014 [a]
Concrete B 25	0.8	NEPD 123N, 2013 [a]
Concrete B 35	1.0	NEPD-332-216N, 2015 [a]
Concrete B 45	1.0	NEPD-334-218-N, 2015 [a]
Concrete reinforcement	8.8	NEPD-348-237E, 2015 [a]
Fibreboard, soft, wind barrier	13.9	NEPD 213N, 2011 [a]
Mortar, dry	1.3	NEPD 00289E, 2014 [a]
PE-foil waterproofing	65.0	NEPD-341-230-N, 2015 [a]
Rockwool	13.4	NEPD 00131E rev1, 2013 [a]
Steel sheet	46.0	NEPD 00178N rev1, 2013 [a]
Steel sheet, galvanized	65.3	NEPD 00171N rev1, 2013 [a]
Steel, based on ore	19.2	NEPD 00235E, 2014 [a]
Timber construction	4.1	NEPD 084N rev1, 2012 [a]
Timber, cladding	4.8	NEPD 082N rev1, 2012 [a]

[a] Norwegian EPD environmental product declarations at: www.epd-norge.no

4.2.3 Functional units

Milk includes both fat and protein in varying amounts. To compare milk on the basis of its energy content, the amount of milk mass was standardized to a kg of energy corrected milk (*ECM*) (Sjaunja et al., 1991), based on its fat and protein content:

$$ECM\ [\mathrm{kg}] = milk\ [\mathrm{kg}]\ ((38.3\ fat\ [\mathrm{g\ kg^{-1}}] + 24.2\ protein\ [\mathrm{g\ kg^{-1}}] + 783.2) / 3140) \qquad (4.1)$$

Norwegian full-cream milk is sold with 3.9 % fat and 3.3 % protein and has a metabolizable energy content of 2.78 MJ kg^{-1} (Norwegian Food Safety Authority, 2015). Per1 kg carcass of cow, the content of nutritional energy is estimated as 6.47 MJ per kg (Heseker and Heseker, 2013). The functional unit of 1.0 MJ metabolizable energy is thus contained in 0.36 kg of milk or 0.15 kg of meat or any combination of 1.0 MJ milk and meat. The farmers in our study produced milk and animals for slaughter or as live animals. The methods of dealing with these co-products have an impact on the results (Cederberg and Stadig, 2003), but in this article we use a system expansion, summing up the content of metabolizable energy for human consumption in sold milk and meat gain.

4.2.4 Energy in- and outputs and energy intensities

Primary energy embodied in the purchased inputs on the dairy farms (SI_{pDF}) was calculated as the sum of energy needed for production and transportation to farm gate of concentrates, milkpowder, bought round bales, bought animals, entrepreneurial baling, PE-foil, fuel, electricity, silage additives, pesticides, bedding, transport of concentrates, fertiliser and lime (see Table 4.3 and Eq. (4.2)).

$$SI_{pDF} = I_{aa} + I_{ab} + I_{ac} + \ldots + I_{am} + I_{an} = \sum_{i=a}^{n} I_{pi} \tag{4.2}$$

The conditions for producing roughages were estimated based on local field trials, fertilisation schemes and information from the local extension service. The DM roughage yield per hectare off-farm area was calculated as the average harvested yield from the farms to be 4200 kg DM ha^{-1} for conventional and 2940 kg DM ha^{-1} for organic farms. The conditions were comparable to those described by Strid and Flysjø (2007), so we used the same values for primary energy needed per kg DM (1.70 MJ kg^{-1} DM) for roughage bought from conventional farms. For organic roughage we reduced the value by the reported 0.37 MJ kg^{-1} for mineral fertilizer and thus estimated the value to be 1.33 MJ kg^{-1} DM. The off-farm area needed to produce roughage was calculated by dividing the amount of imported roughage by the harvested yield. Values for the area and primary energy needed for production of ingredients in concentrates were taken from ecoinvent V 3.2 (Weidema et al., 2013). The off-farm area needed, was calculated by multiplying the mass of each ingredient with the land occupation ($m^2\ kg^{-1}$). The energy for bought animals includes the energy needed to raise the animals. We used the average energy intensity calculated in this study for conventional (2.6 MJ/MJ) and organic (2.1 MJ/MJ) farms to produce metabolic energy in 1 kg carcass, and multiplied this value with the expected carcass share (53 % of liveweight) of bought animals' weight.

We calculated three energy intensities with all sold milk and meat gain (SO_{mm}) as output (Table 4.3): energy intensity on yearly purchased inputs ($\varepsilon_{i\text{-}pDF}$), energy intensity on purchased inputs plus machinery and buildings (infrastructure) ($\varepsilon_{i\text{-}pDF+Infra}$), and energy intensity for all inputs ($\varepsilon_{i\text{-}all}$). Two energy intensities were calculated, where production of milk and meat gain on free rangeland was subtracted from the output (NO_{mm}): energy intensity on purchased inputs ($\varepsilon_{i\text{-}pDF\text{-}FR}$), and energy intensity on purchased inputs plus infrastructure ($\varepsilon_{i\text{-}pDF+Infra\text{-}FR}$).

The five energy intensities are dimensionless and calculated as quotients with the input of primary energy from cradle to farm gate as nominator and the metabolic energy output from milk and meat gain as denominator. Similar to energy intensities, nitrogen intensities were calculated as quotients with the input of nitrogen used in production on the dairy farm ($N_{i\text{-}pDF}$) as nominator and the output of nitrogen for human consumption from milk and meat gain as denominator (chapter 2.2.4).

In addition to calculating the energy intensities, correlation matrices were calculated to analyse which variables influenced the different energy intensities and whether variables were correlated to each other. The correlation matrices were in addition used to preselect variables for the regressions to find important variables influencing energy intensities calculated on primary energy for purchase ($\varepsilon_{i\text{-}pDF}$) and all input ($\varepsilon_{i\text{-}all}$). The basic forms for the two regression functions were:

$$\varepsilon_{i-pDF} = \alpha + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_p X_p \tag{4.3}$$

$$\varepsilon_{i-all} = \alpha + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_p X_p \tag{4.4}$$

4.2.5 Statistics

For statistical analysis, the software RStudio® (version 0.99.893, www.rstudio.com) was used in combination with R® (version 3.2.4, www.r-project.org).

The software was used for linear regressions, t-tests and correlation matrices. Correlation was calculated as Pearson’s r and resulting matrices were analysed to see how variables were linked to different energy intensities. The matrices allow in addition to see the correlations between variables. The matrices were created for all 20 farms and separately for conventional and organic farms, because different variables were significant for the two modes of production. Some variables had different strength and direction and some variables were only significant due to the differences between the two modes of production. For descriptive statistics as mean, standard deviation and figures, Microsoft® Excel® 2013 was used in addition.

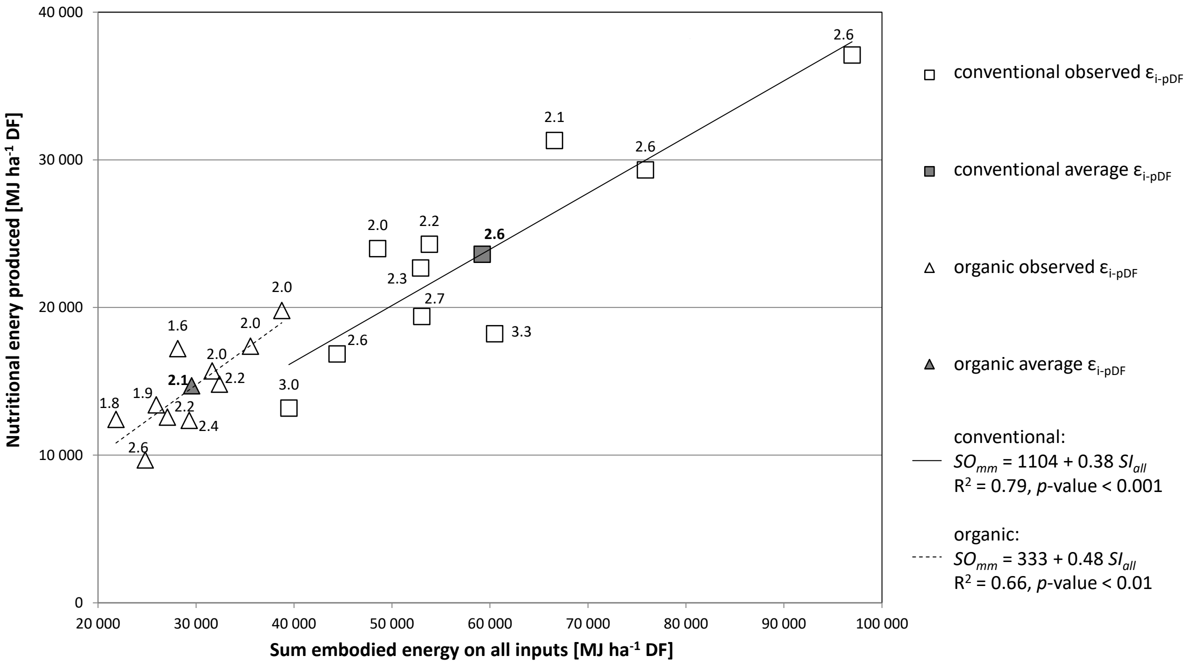
4.3 Results

On average, organic farms produced with a lower energy intensity on all inputs ($\varepsilon_{i\text{-}all}$, Table 4.3) than conventional farms. The summed energy input on organic dairy farm area was significantly lower compared to conventional, independent if calculated on purchased inputs, the sum of purchased inputs and machinery and buildings (infrastructure), and all inputs.

4.3.1 Contribution of purchase on produce and energy intensity

An increased energy input from all inputs (SI_{all}) with one MJ ha^{-1} DF on conventional farms, resulted in an increase of production of metabolizable energy (SO_{mm}) with 0.38 ± 0.07 MJ ha^{-1} DF and of 0.48 ± 0.12 MJ ha^{-1} on organic farms (Fig. 4.2). Thus an increasing energy input was slightly better utilized for producing metabolizable energy on organic than on conventional farms. Although some organic farms produced as much metabolizable energy per dairy farm hectare as the conventional ones with lowest production, no organic farm reached the average production on conventional farms.

Fig. 4.2 Production of metabolizable energy in milk and meat gain per dairy farm (DF) area (vertical axis) in relation to embodied energy input on all input per dairy farm area (horizontal axis). Labels display energy intensities on all embodied energy input. Values are given for conventional and organic farms, with average and linear regression for each group.



4.3.2 Energy intensity

The energy intensity on purchase was 1.4 ± 0.3 for organic and 2.1 ± 0.2 for conventional farms ($\varepsilon_{i\text{-}pDF}$; Table 4.3). The different energy intensities calculated for the average of the organic farms were lower than those for conventional farms, but within each group of conventional and organic farms we found high and low energy intensities independent of the energy input (Fig. 4.2).

Organic farms produced with lower energy intensities than conventional ones, but the share of infrastructure of total energy use was higher for the organic farms (Fig. 4.3). For the farm with the lowest average milking yield (2980 kg ECM cow^{-1} year^{-1}), including infrastructure increased the intensity based on purchase ($\varepsilon_{i\text{-}pDF}$) by nearly 90 %. On the conventional farm with the highest milk yield (9350 kg ECM cow^{-1} year^{-1}), infrastructure increased the intensity based on purchase by 17 %. Of the entire amount of primary energy consumption for the produce on dairy farms, infrastructure were found to vary from 15 % to 43 %. The average value on conventional farms was 19 % and on the organic farms 29 %.

Table 4.3 Amount of primary energy needed to produce inputs and content of metabolic energy in outputs per dairy farm (DF) hectare per year.
Average values and standard deviation for conventional and organic farms, respectively. The inputs are in MJ primary energy and outputs in MJ metabolizable energy per dairy farm hectare. For sums and energy intensities (ε), the formulas are given.

		conventional		organic		t-test[a]
	Index and formula	average	std. dev.	average	std. dev.	con org
Inputs, primary energy needed to produce		[MJ ha^{-1} DF]				
Purchase dairy farm (DF)	I_p					
Concentrates	I_{pa}	18748	7304	7554	2747	***
Milkpowder	I_{pb}	602	610	0	511	*
Imported roughage	I_{pc}	411	644	693	398	n. s.
Bought animals	I_{pd}	136	151	95	64	n. s.
Entrepreneurial baling	I_{pe}	604	485	189	325	*
PE-foil	I_{pf}	1382	789	921	818	n. s.
Fuel	I_{pg}	7575	3119	4247	1730	**
Electricity	I_{ph}	7684	3125	6035	2208	n. s.
Silage additives	I_{pi}	1679	1338	601	803	*
Pesticides	I_{pj}	32	13	0	26	***
Bedding	I_{pk}	16	16	37	49	n. s.
Transport	I_{pl}	407	149	190	87	***
Fertiliser	I_{pm}	8799	2571	153	2520	***
Lime	I_{pn}	88	90	49	66	n. s.
Sum MJ-purchase DF	$SI_{pDF} = \sum_{i=a}^{n} I_{pi}$	48164	15001	20764	9229	***
Values for infrastructure per year						
Tractors and other machinery	I_b	7668	2182	5821	1727	n. s.
Stables	I_c	3052	1110	2659	537	n. s.
Other agric. buildings	I_d	319	147	294	172	n. s.
Free rangeland (FR), MJ in milk and meat gain	I_{FR}	770	821	478	747	n. s.
SUM purchase, machinery, buildings	$SI_{pDF+Tech} = SI_{pDF} + I_b + I_c + I_d$	59203	16847	29538	8785	***
SUM all inputs	$SI_{all} = SI_{pDF+Infra} + I_{FR}$	60743	17802	30494	8690	***
Outputs, metabolizable energy		[MJ ha^{-1} DF]				
Sold milk, incl priv.	O_{milk}	20456	6457	12619	4146	**
Meat gain	O_{meat}	3174	1107	1911	478	**
Sum output (milk and meat gain)	$SO_{mm} = O_{milk} + O_{meat}$	23631	7273	14529	4102	**
Net output without production free rangeland (FR)	$NO_{mm} = O_{milk} + O_{meat} - I_{FR}$	22861	6869	14052	4368	**
Energy intensities		[MJ MJ^{-1}]				
Energy intensity purchase	$\varepsilon_{i\text{-}pDF} = SI_{pDF}/SO_{mm}$	2.1	0.2	1.4	0.3	***
Energy intensity purchase and techn. equipment	$\varepsilon_{i\text{-}pDF+Tech} = SI_{pDF+Infra}/SO_{mm}$	2.6	0.4	2.1	0.3	**
Energy intensity all input	$\varepsilon_{i\text{-}all} = SI_{all}/SO_{mm}$	2.6	0.4	2.1	0.3	*
Energy intensities without free rangeland (FR)						
Energy intensity purchase DF - FR	$\varepsilon n_{i\text{-}pDF} = SI_{pDF}/NO_{mm}$	2.1	0.3	1.5	0.3	***
Energy intensity purchase and techn. equipment - FR	$\varepsilon n_{i\text{-}pDF+Tech} = SI_{pDF+Infra}/NO_{mm}$	2.6	0.4	2.1	0.4	*

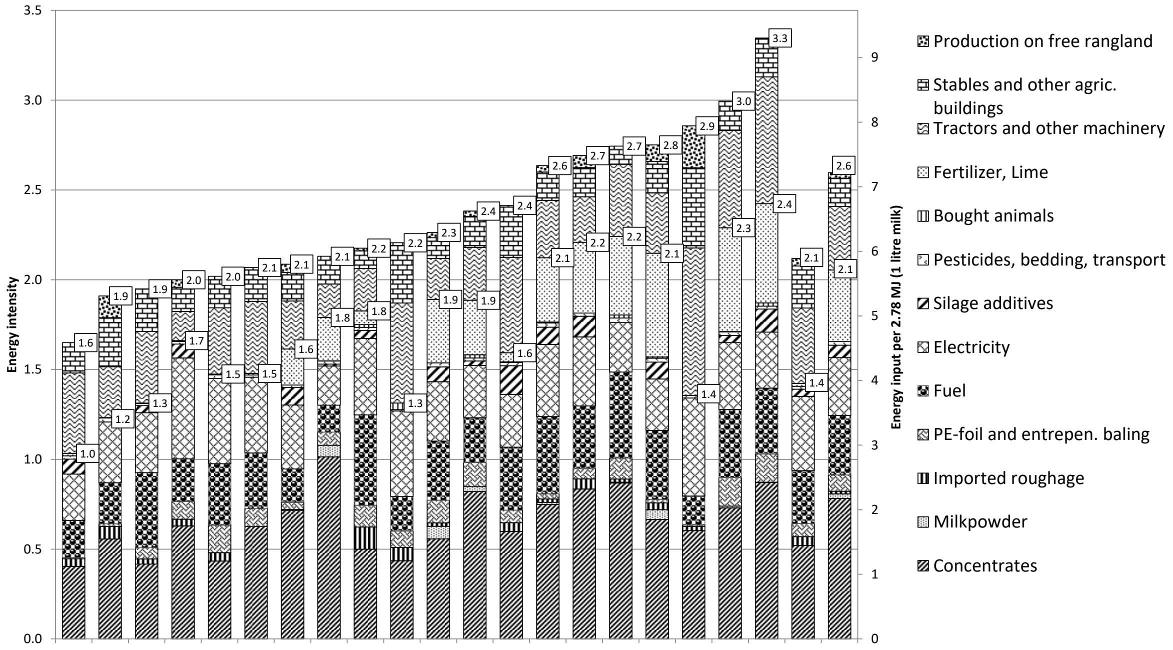
[a] significant at level: *** < 0.001; ** < 0.01; * < 0.05

[b] For production of milk and meat on free rangeland, the metabolic energy in the product was used. The value of primary energy as defined in this study was zero. Production on free rangeland can be considered as both input and output.

Fig. 4.3 Energy intensity is the amount of primary energy needed to produce 1 MJ metabolizable energy in delivered milk and meat gain (left axis).

Values for conventional (con) and organic (org) dairy farms and the contribution of energy from different inputs. The lower label in each bar displays the energy intensity on purchase ($\varepsilon_{i\text{-}pDF}$) and the upper label the energy intensity on all energy input ($\varepsilon_{i\text{-}all}$). Farms are sorted by increasing energy intensity for total energy input.

The right axis is scaled to show energy intensity to produce 2.78 MJ metabolizable energy, corresponding to the metabolic energy content of 1 litre milk. Below the figure, milk yield per cow in kg ECM cow^{-1} year^{-1} and energy intensities without free rangeland.



	org	org	org	org	org	org	con	con	org	org	con	con	org	con	con	con	con	org	con	con	org aver.	con aver.
Milk yield ECM cow^{-1} year^{-1}	7090	4080	5120	7330	8260	7510	8650	9160	7710	4380	9350	8350	5520	8170	7930	8440	7120	2980	7730	7810	6000	8270
$\varepsilon n_{i\text{-}pDF+Tech}$	1.6	2.0	1.9	2.0	2.0	2.0	2.1	2.1	2.2	2.2	2.3	2.4	2.4	2.7	2.8	2.7	2.9	3.3	3.0	3.3	2.1	2.6
$\varepsilon n_{i\text{-}pDF}$	1.0	1.4	1.3	1.7	1.5	1.5	1.7	1.8	1.9	1.3	1.9	1.9	1.6	2.2	2.4	2.2	2.4	1.8	2.3	2.4	1.5	2.1

4.3.3 Milk yield and energy intensities

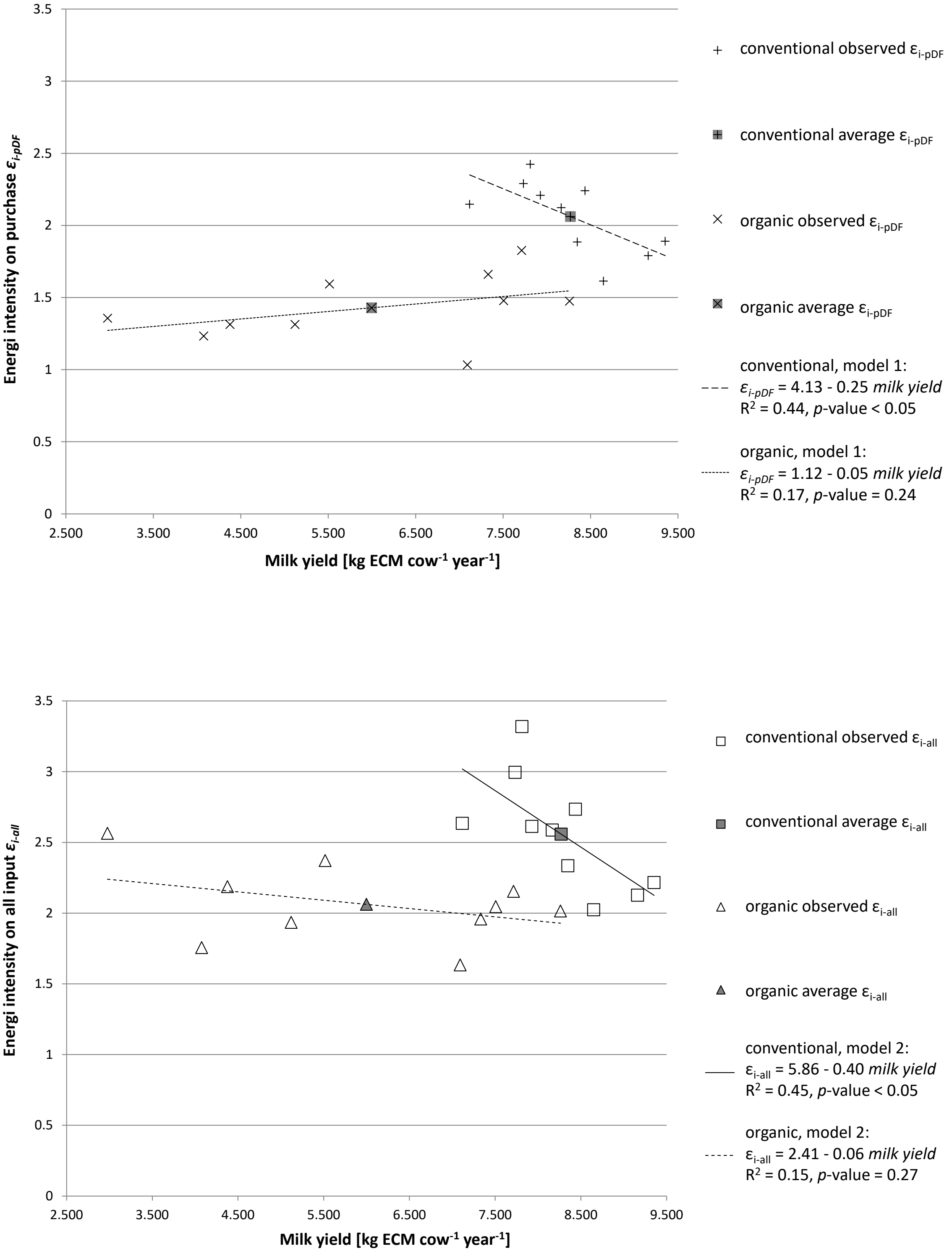
The effect of milk yield on energy intensities was tested by regressions (Table 4.4) for conventional and organic farms, respectively. For conventional farms there was a tendency that increasing milk yields per dairy cow resulted in lower energy intensities on purchased inputs (ε_{ipDF}, Fig. 4.4a) and on all energy ($\varepsilon_{i\text{-}all}$, Fig. 4.4b). One conventional farm produced with slightly lower intensity ($\varepsilon_{i\text{-}all} = 2.0$) than the average for the organic farms, and two other farms close to the average for organic farms (Fig. 4.4b). On the organic farms, the energy intensities was not influenced by the variation in milk yield (3.0 to 8.3 t ECM). But there was a bigger influence from infrastructure on energy intensity on organic farms, especially on those with low milk yields.

Table 4.4 Energy intensities for milk delivered and meat gain as affected by milk yield.

Model nr, production	Coefficient	Coefficient estimate	Standard error	*p*-value[a]	R^2 (model)	Variables
1, energy intensity on purchase, conventional farms, eq. (4.4)				*	0.44	
	α	$4.13e^{+00}$	$8.27e^{-01}$	**		
	β_1	$-2.50e^{-01}$	$9.97e^{-02}$	*		X_1 = milk yield (t ECM cow^{-1} year^{-1})
1, energy intensity on purchase, organic farms, eq. (4.4)				n.s.	0.17	
	α	$1.12e^{+00}$	$2.53e^{-01}$	**		
	β_1	$5.19e^{-02}$	$4.05e^{-02}$	n.s.		X_1 = milk yield (t ECM cow^{-1} year^{-1})
2, energy intensity on all input, conventional farms, eq. (4.5)				*	0.45	
	α	$5.86e^{+00}$	$1.29e^{+00}$	**		
	β_1	$-4.00e^{-01}$	$1.56e^{-01}$	*		X_1 = milk yield (t ECM cow^{-1} year^{-1})
2, energy intensity on all input, organic farms, eq. (4.5)				n.s.	0.15	
	α	$1.13e^{+01}$	$4.49e^{+00}$	*		
	β_1	$-2.58e^{+00}$	$2.16e^{+00}$	n.s.		X_1 = milk yield (t ECM cow^{-1} year^{-1})

[a] significant at level
*** *p*-value < 0.001; ** *p*-value < 0.01; * *p*-value < 0.05

Fig. 4.4a, b Energy intensities in relation to milk yield. Values for conventional and organic farms, with average and linear regression on milk yield for each group.



4.3.4 Correlation between variables tested

To investigate the dependence between multiple variables on intensities, correlation matrices were calculated (data not shown). On the conventional farms, was a high correlation between nitrogen (N) intensities (chapter 2.3.3) and energy intensities on purchase ($\varepsilon_{i\text{-}pDF}$). On conventional farms, an increased amount of dairy farm area was positively correlated with higher energy intensities on purchased inputs and infrastructure ($\varepsilon_{i\text{-}pDF+Infra}$) and all inputs ($\varepsilon_{i\text{-}all}$). On organic farms, more dairy farm area was correlated with higher energy intensities of purchased inputs ($\varepsilon_{i\text{-}pDF}$). Larger conventional farms, measured in dairy farm area and number of cows, had higher weight of tractors (kg ha^{-1} year^{-1}), more likely used milking robots, used less working hours per cow (h cow^{-1} year^{-1}), and less working hours per metabolizable energy produced (h MJ^{-1} year^{-1}). Larger organic farms were positively correlated with a greater distance to the fields (m ha^{-1}), a higher share of concentrates in the feed ration, a lower share of silage stored in silage-towers, less human working hours per cow (h cow^{-1} year^{-1}), less human working hours per metabolizable energy produced (h MJ^{-1} year^{-1}), a lower energy uptake by grazing relative to the entire energy uptake by cattle, and a lower return to labour per dairy farm area and per metabolizable energy produced. On organic farms, a higher energy uptake by grazing relative to the entire energy uptake by cattle was strongly negatively correlated with the share of concentrates in the feed ration, delivered milk (kg ECM cow^{-1} year^{-1}), and the number of cows on the farm. On the other hand, grazing on organic farms was strongly positively correlated with using more working hours per hectare (h ha^{-1} year^{-1}) and more working hours per metabolizable energy produced (h MJ^{-1} year^{-1}).

The energy intensity on purchase on the 20 dairy farms (Model 3, Table 4.5) was highly correlated with the nitrogen intensity on purchase ($N_{i\text{-}pDF}$). Since conventional and organic farms produce with different N intensities (Table 2.2), the explanation of this model mainly reflects the different nitrogen intensities between conventional and organic farms, thus more models were tested. The conventional farms had a higher energy intensity on purchase ($\varepsilon_{i\text{-}pDF}$) when more diesel ha^{-1} was used, they had a higher share of N fertiliser ha^{-1} and a lower share of N fixed by clover ha^{-1} of all N-input ha^{-1} dairy farm (Model 4, Table 4.5). On organic farms, the energy intensity on purchase ($\varepsilon_{i\text{-}pDF}$) increased with lower harvestable yields ha^{-1} and an increased use of PE-foil for silage (Model 5, Table 4.5).

Table 4.5 Variables influencing the energy intensities on purchase on dairy farms ($\varepsilon_{i\text{-}pDF}$).

Model nr., production	Coefficient	Coefficient estimate	Standard error	p-value[a]	R^2 (model)	Variables
3, energy intensity on purchase, all 20 farms, eq. (4.3)				***	0.88	
	α	$8.87e^{-01}$	$8.11e^{-02}$	***		
	β_1	$2.06e^{-01}$	$1.79e^{-02}$	***		X_1 = N-intensity $N_{i\text{-}pDF}$
4, energy intensity on purchase, conventional farms, eq. (4.3)				**	0.91	
	α	$9.10e^{-01}$	$2.45e^{-01}$	***		
	β_1	$1.47e^{-03}$	$4.56e^{-04}$	**		X_1 = Diesel ($l\ ha^{-1}\ year^{-1}$)
	β_2	$1.77e^{+00}$	$3.64e^{-01}$	***		X_2 = Fertiliser N/all N-input DF
	β_3	$-7.96e^{-01}$	$2.68e^{-01}$	**		X_3 = N fixed by clover/all N-input DF
5, energy intensity on purchase, organic farms, eq. (4.3)				**	0.86	
	α	$1.86e^{+00}$	$1.55e^{-01}$	***		
	β_1	$-1.37e^{-04}$	$3.15e^{-05}$	***		X_1 = Harvestable yield (kg DM $ha^{-1}\ year^{-1}$)
	β_2	$1.32e^{-02}$	$3.07e^{-03}$	***		X_2 = PE-foil used (kg $ha^{-1}\ year^{-1}$)

[a] significant at level
*** p-value < 0.001; ** p-value < 0.01; * p-value < 0.05

Testing the Nitrogen intensity $N_{i\text{-}pDF}$ as a variable, explaining the energy intensity $\varepsilon_{i\text{-}all}$ on all inputs showed a lower coefficient of determination (Model 6, Table 4.6).

On conventional farms, the energy intensity $\varepsilon_{i\text{-}all}$ on all inputs could be described satisfactorily by model 7 with only two variables ($R^2 = 0.96$). The energy intensity $\varepsilon_{i\text{-}all}$ was positively correlated with the sum of tractorweight ha^{-1} and N intensity on purchase $N_{\text{i-pDF}}$. For organic farms, model 8 had a coefficient of determination of 0.85, describing the energy intensity $\varepsilon_{i\text{-}all}$ on all inputs. The energy intensity $\varepsilon_{i\text{-}all}$ was positively correlated with the floor area per cow in the barn, lower liveweight of the cows and less nitrogen fixated by clover as share of all nitrogen used on the dairy farm.

Table 4.6 Variables influencing the energy intensities on primary energy for all inputs on dairy farms ($\varepsilon_{i\text{-}all}$).

Model nr., farms	Coefficient	Coefficient estimate	Standard error	*p*-value[a]	R^2	Variables
6, energy intensity on all inputs, all 20 farms, eq. (4.4)				***	0.53	
	α	$1.65e^{+00}$	$1.76e^{-01}$	***		
	β_1	$1.77e^{-01}$	$3.90e^{-02}$	***		X_1 = N-intensity $N_{\text{i-pDF}}$
7, energy intensity on all inputs, conventional farms, eq. (4.4)				***	0.96	
	α	$8.46e^{-01}$	$1.71e^{-01}$	***		
	β_1	$1.62e^{-02}$	$2.41e^{-03}$	***		X_1 = Tractor-weight (kg ha^{-1} $year^{-1}$)
	β_2	$2.00e^{-01}$	$2.91e^{-02}$	***		X_2 = N-intensity $N_{i\text{-}pDF}$
8, energy intensity on all inputs, organic farms, eq. (4.4)				**	0.85	
	α	$3.93e^{+00}$	$4.60e^{-01}$	***		
	β_1	$2.10e^{-02}$	$8.96e^{-03}$	*		X_1 = Floor area in barn per cow (m^2 cow^{-1})
	β_2	$-3.34e^{-03}$	$7.64e^{-04}$	***		X_2 = Liveweight cow (kg cow^{-1})
	β_3	$-6.91e^{-01}$	$1.78e^{-01}$	***		X_3 = N fixed by clover/all N-input on DF

significant at level
*** *p*-value < 0.001; ** *p*-value < 0.01; * *p*-value < 0.05

4.4 Discussion

4.4.1 Energy intensity

In this study, different energy intensities were calculated on purchased inputs, machinery and also buildings, so the results can be compared with other European studies. As in this study, in all studies analysing both conventional and organic dairy farms, lower energy intensities were found for organic milk production.

We found only one study including energy from purchase and infrastructure with data on conventional and organic milk production (Refsgaard et al., 1998). They found for sandy soils in Denmark an energy intensity of 3.6 MJ kg^{-1} ECM on conventional and 2.7 MJ kg^{-1} ECM on organic dairy farms, much lower than our results of 7.2 MJ kg^{-1} ECM and 5.8 MJ kg^{-1} ECM, respectively. The much lower values in Denmark can be due to higher yields in Denmark compared to Norway, but also due to the calculation of the quantity of machinery and buildings were expected and not measured on farm. Another effect may be that

Norwegian dairy farming can be characterized by intensive use of mechanisation and high fossil fuel (Vigne et al., 2013).

Other European studies including all energy input only include conventional farms and are from Switzerland and Germany. Including the effect of building materials and feed sources, Erzinger et al. (2004) found 4.1 to 6.0 MJ kg^{-1} ECM and Hersener et al. (2011) 4.8 to 6.0 MJ kg^{-1} ECM. Modelling farms for future dairy farming in Germany, Kraatz (2012, 2009) found values from 3.3 to 4.0 MJ kg^{-1} ECM. These lower values may be the result of much higher yields compared to Norway and the effect of less embodied energy in stables, modelled for 180 cows. Another reason may be the use of standard values for the field operation processes, which can underestimate, e.g., diesel use on real farms by nearly 50 % (Refsgaard et al., 1998).

Including both the purchase and machinery on French dairy farms, van der Werf et al. (Werf et al., 2009) found lower energy intensity and on average a smaller difference between conventional and organic production (2.8 and 2.6 MJ/kg ECM) than in our study (6.7 and 5.2 MJ/kg ECM), but as we did, Werf et al. also found a high variation within both groups. As Meul et al. (2007), we found conventional dairy farms combining high production with low energy use to be most energy efficient.

4.4.2 Effect of milk yield on energy intensities

The effect of milk yield on energy intensities was different for the two modes of production in this study. For conventional farms, there was a tendency for energy intensities to decrease when milk yield increased (Table 4.4 and Fig. 4.4a, b). This was expected, based on different studies (Garnsworthy, 2004; Gerber et al., 2011; Kraatz, 2012; Yan et al., 2013). As found in the literature review by Smith et al. (2015), we found that organic production produced on average better than conventional production, but not only on area basis (energy intensity per area), but also on product basis (energy intensity per unit product). But we did not find other publications comparable to our finding that energy intensities on organic farms were unaffected of milk yield.

4.4.3 Larger farms

We could not find reduced energy intensities on farms with increasing farm size, measured in herd size or area, as Hersener et al. (2011) did for comparable farms in Switzerland. Rather, we found conventional farms with increasing area to have higher energy intensities, both calculated on purchase ($\varepsilon_{i\text{-}pDF}$) and on all input ($\varepsilon_{i\text{-}all}$) and to have more tractorweight (kg ha^{-1} year^{-1}). For organic farms the overall energy intensity did not increase with increasing farm area, but these farms used more diesel (l ha^{-1}). Due to the narrow valleys in the region, combined with small fields and rented area, an increase in farm area often increases the distance to the fields significantly, requiring more diesel for transport. The climate, with few days for harvesting under optimal conditions, might explain why farmers buy bigger tractors, thus being able to harvest more area within the available “harvest window”.

4.4.4 Increased grazing can contribute to reduce energy intensity

Grazing can contribute to reducing energy intensity as found by O’Brien et al. (2012), Kraatz (2012, page 99) and Vigne et al. (2013). Not surprisingly, we found for all farms, that more energy uptake by grazing relative to the entire energy uptake by cattle reduced the use of PE-foil for silage (kg PE-foil ha^{-1} year^{-1}). Grazed feed does not have to be harvested or packed as round bales. Grazing free rangeland had on little effect on reducing the energy intensities calculated for the average for conventional and organic farming. But for some farms there was a clear positive effect of grazing free rangeland, e.g. for the organic farm with the highest overall energy intensity ($\varepsilon_{i\text{-}all}$ = 2.9, Fig. 4.3), the intensity increased to $\varepsilon n_{i\text{-}pDF+Infra}$ = 3.3, for the production without free rangeland. Increased grazing on native grassland and free rangeland complies also with van Kernebeek et al. (2016), to use land unsuitable for crop production by animals for food production.

4.4.5 Importance of buildings and machinery

On two of the organic farms with below-average milk yields, the amount of embodied energy from infrastructure contributed up to 43 % of the entire primary energy used. It is difficult to reduce the amount of embodied energy in buildings and machinery in the short run. Good maintenance for longer lifetime expectancy of buildings and machinery would gradually reduce the share of embodied energy from infrastructure in dairy products. When making investments, focus on material savings and increased use of materials with lower primary energy demand during production, as for example wood instead of concrete, would reduce the relative amount of primary energy for the future, but so far, it is still difficult for farmers to get information on how to reduce embodied energy when building new barns.

Some arguments for why embodied energy from buildings is not included in LCA studies are mentioned (Harris and Narayanaswamy, 2009). These include: small influence on overall results (Flysjö et al., 2011), the inclusion of embodied energy is time consuming, there is a lack of data, or that buildings are comparable for the different farms in the study and no differences are expected (Cederberg and Mattsson, 2000; Thomassen et al., 2008). Including buildings and machinery, Rossier and Gaillard (2004) found values for energy intensity for producing milk from 3.7 MJ/kg ECM to 12.3 MJ/kg ECM. Even if little can be done to reduce the amount of embodied energy from infrastructure in the medium term (Lebacq et al., 2013), information on the actual status and how to reduce embodied energy is crucial, because infrastructure can have an important contribution to the overall energy use. Also, it is possible to build barns with a lower amount of embodied energy (Dux et al., 2009; Koesling et al., 2015).

Comparing energy intensity in conventional and organic dairy farming based only on purchase, would show organic dairy production to be highly superior to conventional, having an energy intensity on purchase of only 67 % of the energy intensity found on conventional farms ($\varepsilon_{i\text{-}pDF}$ 1.4 for organic compared to 2.1 for conventional). However, when including embodied energy for infrastructure, the energy intensity on organic farms was 81 % of the figure for conventional farms ($\varepsilon_{i\text{-}all}$ 2.1 to 2.6, respectively, Fig. 4.3). It is important to be aware, that focusing on energy intensity on purchase will result in other recommendations to improve intensity than focusing on energy intensity on all inputs.

4.5 Conclusion

The objectives of this study were to analyse if there are differences in the energy intensities in conventional and organic dairy farming, and if the intensities are influenced by machinery and buildings. If different energy intensities were found for the two different production modes, it should be analysed if different solutions should be chosen to reduce the energy intensities.

Energy intensities are used to describe the amount of embodied energy needed to produce a unit of metabolizable energy in milk and meat. We found that organic dairy farms produced milk and meat with significantly lower energy intensities than conventional farms.

Because the share of embodied energy from machinery and buildings on the dairy farms varied from 15 % to 44 % of the entire consumption of embodied energy, strategies to reduce energy intensities in dairy farming should not only focus on embodied energy on purchase but also include embodied energy on machinery and buildings. For conventional and organic dairy farms there are different strategies for reducing the energy intensity on all inputs. Conventional farms can reduce energy intensity by reducing tractorweight (measured as weight of all tractors on farm per dairy farm area) and improving nitrogen utilization, by a reduced use of nitrogen fertilizer as an important contribution. On organic dairy farms, energy intensity can be reduced by reducing embodied energy in barns, using higher-yielding cows and more nitrogen fixation by clover.

The high variation of energy intensity an all inputs from 1.6 to 3.3 (4.5 to 9.3 MJ kg^{-1} milk) found on the 20 farms shows the potential for producing with low energy input and underlines that individual farm analyses are preferable as a basis for developing individual solutions to reduce energy intensity.

Using energy intensities highlights the influence of embodied energy from different inputs and enables the development of solutions to improve the farms overall energy utilization.

4.6 Acknowledgements

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5 Additional results on area- and economic intensity

While the focus of this thesis was restricted to environmental sustainability, additional results will be presented in regard of area and the economic intensity. This seems to be important under the need to feed the expected 9 billion people on earth in 2030. While organic farming is considered to contribute among others to energy savings, CO2 abatement and healthy foods (Gomiero et al., 2008), it is important to focus on sufficient yields and satisfactory income for farmers.

5.1 Material and methods

In regard of area, the different areas are presented in chapter 4.2.1.1. and the average amount of dairy farm and dairy system area in chapter 4.2.1.3. To calculate the area intensity, the area is divided by the amount of metabolizable energy produced (delivered milk and meat gain) and multiplied by 2.78. Thus the area intensity is an indicator for the area needed to produce the equivalent of one litre of milk, containing 2.78 MJ metabolizable energy.

$$\text{area intensity}_{DF}\ [m^2\ l\ milk^{-1}] = \text{dairy farm area}\ [m^2] / \text{metabolizable energy} \times 2.78\ [MJ] \quad (5.1)$$

$$\text{area intensity}_{DS}\ [m^2\ l\ milk^{-1}] = \text{dairy system area}\ [m^2] / \text{metabolizable energy} \times 2.78\ [MJ] \quad (5.2)$$

The return to labour per recorded working hour [€ h^{-1}] was presented in chapter 4.2.1.3. To calculate this value, first all costs, except for labour, were subtracted from farm revenues and then this value was divided by all working hours on the dairy farm. Revenues include sold milk and animals, sold silage, government payments, organic farming payments and other incomes for the farm. Costs include purchased feed, variable costs for forage production, veterinary and medicine, machinery[6], farm buildings[7], general overheads[8], land and milk quota and interest[9], but no costs for labour.

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[6] E.g. office expenses, fees for accounting, advisory costs, insurance fees

[7] Running and ownership costs of all farm buildings and equipment installed in the buildings

[8] E.g. office expenses, fees for accounting, advisory costs, insurance fees

[9] Land, purchased milk quota, buildings, equipment, machinery and breeding livestock at a rate of 3 percent. Farm asset values for the year are calculated by averaging the beginning and ending total asset values from the farm balance sheets.

The economic intensity was calculated by dividing all costs except for labour by all farm revenues. A higher economic intensity indicates that the share of revenues which can be used to pay for used working hours is lower than with a lower economic intensity. An economic intensity of 0.5 indicates that of 10 € revenue, 5 € can be used to pay for the working hours. If the economic intensity is 0.9, only 1 € can be used to pay for the working hours.

$$\text{economic intensity}_{\text{Farm}} = \text{Farm costs } [€] \,/\, \text{Farm revenues } [€] \tag{5.3}$$

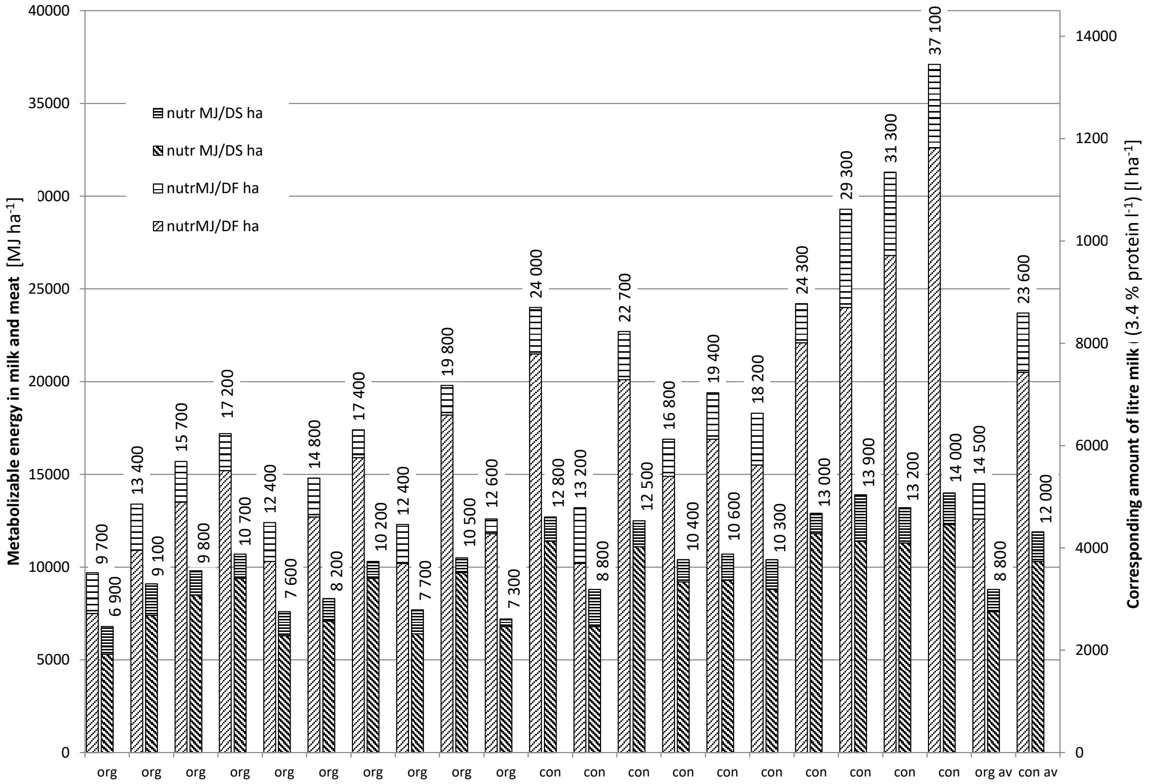
5.2 Effect of off-farm area on area intensity

Usually the production of a farm is used to present the production, as for example the production of roughage, grain or milk per hectare of the farm. But using imported concentrates and roughages occupy off-farm area on other farms. Taking into account not only the area of the dairy farm but also the off-farm area from the dairy system can be useful to demonstrate the contribution of off-farm area to the production on the dairy farm. In figure 5.1 for each farm the amount of metabolizable energy in delivered milk and meat gain per dairy farm area and dairy system area is presented.

The labels show the sum of metabolizable energy in sold milk and meat gain. Milk production accounts on average for 90 % of the entire production of metabolizable energy on conventional and organic dairy farms. Sorting by increased amount of nitrogen from N in net purchase per DF hectare shows that the relation to higher production of metabolizable nitrogen was weak for the conventional farms (see also section 4.3.1). For the organic farms there was no relation found. The right axis is scaled to present the amount of litre of milk per hectare the production would correspond to.

The organic dairy farms produced rounded 14500 MJ ha^{-1} DF (which would comprise to 5200 kg milk ha^{-1} with 2.78 MJ kg^{-1}). This is 61 % of the amount, the conventional produce of rounded 23600 MJ ha^{-1} DF (about 8500 kg milk ha^{-1}). Taking also off-farm area for the dairy system into account, the production per dairy system area is rounded 8800 MJ ha^{-1} DS (about 3200 kg milk ha^{-1}) for organic and 12000 MJ ha^{-1} DS (about 4300 kg milk ha^{-1}) for conventional farms. In relation to the area of the dairy system, organic farms produce 74 % compared to the conventional.

Fig. 5.1 Production of metabolizable nitrogen in delivered milk and meat gain per dairy farm area and dairy system area, sorted by increasing amount of N from net purchase per dairy farm area and amount of total energy use per dairy farm area.



Net purchase DF																						
kg N ha^{-1} DF	41	51	55	58	63	64	73	80	98	103	153	156	201	210	212	228	249	263	269	403	69	234
GJ ha^{-1} DF	13	18	23	18	15	19	26	20	33	23	39	30	43	36	44	44	46	62	56	82	21	48

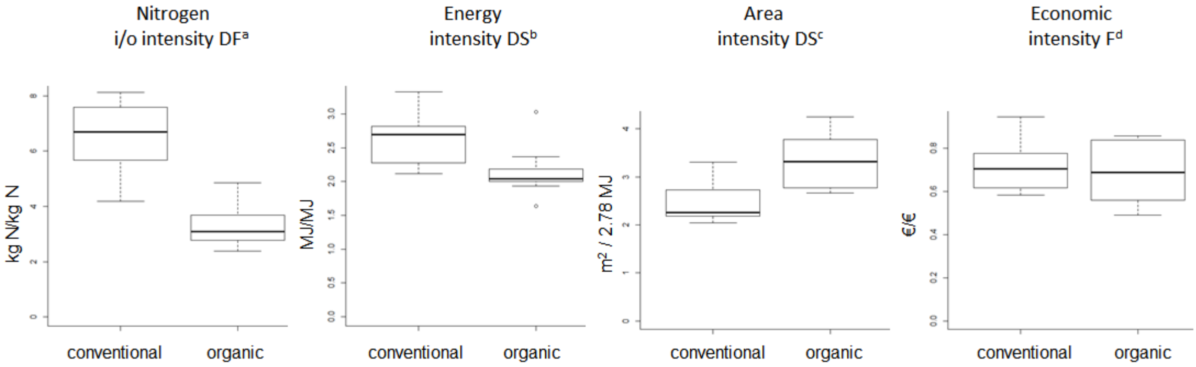
The two conventional farms with highest production of nitrogen per dairy farm area (producing 37100 and 31300 MJ ha^{-1} DF) depend highly on imported feed from off-farm area, only 38 % and 42 % of their production is based on feed production from the dairy farm.

5.3 Comparing intensities for nitrogen, energy, area and economy

In the previous sections, we presented intensities on nitrogen and energy for each farm, as well as the average for organic and conventional production. We calculated in addition intensities for area and economy. All four different intensities are presented in Fig. 5.2 using boxplots for the group of conventional and organic dairy farms. Using boxplots, not the average, but the medians, first and third quartile are presented.

The boxplot in Fig. 5.2 shows that organic farms on average perform much better for nitrogen intensity and better for energy intensity than the conventional (see also the results for intensities in table 2.2 for nitrogen and 4.3 for energy). The advantage for conventional farms is that they produce with a lover area intensity, including farm and off-farm area, than the organic farms. In regard of economic intensity, conventional and organic farms are comparable, but the variation on organic farms is higher than on conventional.

Fig. 5.2 Boxplot for different intensity indicators for organic and conventional dairy farms.



[a] Nitrogen intensity (i/o_{iDF}) on purchase and production of concentrates in relation to metabolizable N in sold milk and meat increase (kg N/kg N).

[b] Energy intensity ($\varepsilon_{i\text{-}pDF+Tech}$) on purchased inputs, machinery and agricultural buildings in relation to metabolizable energy in sold milk and meat increase (MJ/MJ).

[c] Area intensity on dairy system area used per 2.78 MJ metabolizable energy in milk and meat gain (equivalent for 1 litre of milk; m^2/(2.78 MJ)).

[d] Economic intensity for all expenses (except return to labour) on the farm in relation to all income on the farm (€/€).

For the group of conventional and organic respectively, we looked for those farms performing better than average and mean for each of the four intensities. Within the group of conventional we found three and for the group of organic farms we also found three, performing better in regard of all four intensities.

To analyse, if it is possible to point out, if variables can be found being related with a better performance in regard to all intensities, a correlation matrix was conducted (see table 5.1).

Table 5.1 Correlation matrix for the group of conventional and organic farms, all four intensities and selected variables.
Correlation calculated as Pearson's r. Correlation values are only presented when the significance level was below 0.05.

Parameters	**Units**	**Conventional**				**Organic**			
Intensities		Nitrogen intensity	Energy intensity	Area intensity	Economic intensity	Nitrogen intensity	Energy intensity	Area intensity	Economic intensity
Nitrogen i/o intensity purchase DF (i/o_{iDF})	kg N (kg N)$^{-1}$	1	0.833**	0.680*		1			
Energy intensity all input ($\varepsilon_{i\text{-}all}$)	MJ MJ^{-1}	0.833**	1	0.656*			1	0.762*	
Area intensity for metabolizbale energy in delivered milk and meat gain	m^2 (2.78 MJ)$^{-1}$	0.680*	0.656*	1			0.762*	1	
Economic intensity; all expences except return to labourin raltion to all farm income	€ €$^{-1}$				1				1
Farm and work									
Dairy farm area (DF)	ha		0.648*						0.668*
Off-farm area	ha				0.658*				0.705*
Average distance to field	m								0.671*
Tractorweight	kg ha^{-1} year^{-1}		0.814**		0.761*				
Milking robot on farm	dummy								
Embodied energy in machinery and buildings	MJ year^{-1} farm^{-1}				0.869**				
Embodied energy in barn per cow	MJ year^{-1} cow^{-1}		0.671*						
Silage stored in tower in relation to own produced silage	%								
Use of PE-foil til silage	kg ha^{-1} year^{-1}								0.774**
Working hours per cow	h cow^{-1} year^{-1}								-0.943***
Dairy									
Cows per farm	cows farm^{-1}				0.735*				0.735*
DF Stocking rate	cows ha^{-1} DF			-0.679*					
Milk yield	kg ECM cow^{-1} year^{-1}	-0.654*	-0.759*					-0.689*	
Share of concentrates in feed ratio	%		-0.700*						0.746*
Cow weight	kg cow^{-1}				0.638*		-0.664*	-0.790**	
Milk, delivered and used private per farm	kg ECM year^{-1} farm^{-1}				0.688*				0.703*
Milk, delivered and used private per DF area	kg ECM year^{-1} ha^{-1} DF			-0.759*			-0.665*	-0.877***	
Production per DF area (Milk and meat gain)	MJ year^{-1} ha^{-1} DF			-0.874***			-0.669*	-0.932***	
Embodied energy in imported feed	MJ year^{-1}			-0.699*					
Share of energy uptake by grazing in feed ratio	%								-0.642*
Plant production									
Harvestable yield per DF area	kg ha^{-1} DF year^{-1}			-0.712*		-0.819**			
Share of clover in DM yield	%	-0.657*	-0.646*			0.746*			
Nitrogen fertiliser per DF area	kg N ha^{-1} DF year^{-1}				0.645*	0.718*			

Significant at level
*** < 0.001; ** < 0.01; * < 0.05

Looking first at the correlation in-between the four intensities, there was a positive correlation between nitrogen-, energy- and area intensity for the group of conventional farms. On organic farms, only energy and area intensity are positive correlated. For both groups, there was no correlation found between economic intensity and the other intensities.

Since nitrogen and energy intensities have been discussed in chapter 2.3.2 and 4.3.3, we focus here mainly on additional findings. For both conventional and organic farms, an increased amount of off-farm area, an increased number of cows per farm and an increased amount of delivered milk per farm was positive correlated with economic intensity. As stated before, an increased use of fertiliser was not correlated with an decreased area intensity (which would indicate higher yields) on conventional farms. Instead, there is only a positive correlation to economic intensity.

Increased farm area on organic farms is linked to an increased distance to the fields and both is positive correlated to a higher economic intensity. On organic farms the economic intensity was negative correlated with working hours per cow and energy uptake by grazing, while it was positive correlated with the use of PE-foil for silage.

6 Synthesis and general conclusions

6.1 Introduction

On the background of climate change, environmental pollution and restricted fossil energy sources, all human activity has to focus on an improved resource utilization. In Norway, as in many other industrialised countries, dairy products and meat have an important part in human nutrition, and dairy farming is an important element in agriculture. In the coastal regions of Norway, dairy farming contributes to an important share of the added value from agriculture. There is little information about the environmental sustainability of dairy farming in Norway.

To close this gap, the utilisation of nitrogen and energy was analysed on ten conventional and ten organic dairy farms, looking for solutions to increase their utilisation. To reflect the differences in farms found in the region, the farms analysed differed both in farmland area, numbers of cattle, use of concentrates and milking yield as well as fertilisation level and grass yield. In three articles (chapters 2 to 4), the utilisation of nitrogen and energy is described. Significant differences were found between conventional and organic farms, as well as high variation within each of the two groups.

Chapter 2 is about the variations in nitrogen utilisation on the 20 dairy farms. To describe the utilisation and to be able to easily point out the different inputs, intensities are used since they were found to be superior to efficiencies. Intensities describe the amount of inputs needed for a unit of output and thus they are the reciprocals of efficiencies. In case of nitrogen, the input is measured as amount of nitrogen in the different inputs and the output as nitrogen in the products (milk and meat) utilisable as human nutrition. Different nitrogen intensities were calculated based on the different input groups, while the output consisted of delivered milk and meat gain.

As preparatory work for calculating the energy utilisation for the farms in chapter 4, chapter 3 describes how the building construction approach was evolved to calculate embodied energy in agricultural buildings. This approach allows to calculate the amount of embodied energy in the buildings' envelope with a lower work load than using a mass material calculation (e.g. Nielsen and Rasmussen, 1977), but is flexible enough to allow for different shapes and use of different materials.

In chapter 4 the variation of energy utilisation on the 20 dairy farms is described. Also here intensities are used, but the inputs are measured as all primary energy needed from cradle to farm gate, and the output of milk and meat was measured as metabolizable energy for human consumption. Energy inputs were grouped as purchase, machinery, buildings and production on free rangeland.

6.2 Synthesis

To achieve the objectives of this thesis, the utilisation of nitrogen and energy on Norwegian dairy farms was analysed on the same farms in two of the articles (chapters 2 and 4). The work was conducted with a comparable approach, using intensities as an essential indicator for describing how efficient inputs are utilized on the different farms and to look for solutions for an improved utilisation. To be able to estimate the amount of embodied energy in buildings, expected to contribute a significant share of the overall energy demand, we prepared an approach and applied it on the agricultural buildings on the 20 farms in the project. This approach is presented in chapter 3.

The 3 articles are based on 20 Norwegian dairy farms, located in the county Møre og Romsdal, with farm data for the calendar years 2010 to 2012. The farms were chosen to represent the variation found in dairy farming in Norway in regard to farmland area and number of cows, share of concentrates in the fodder ration and milk yield level, in addition to fertilisation level on conventional farms. Since the conditions in this region are comparable to other areas in Norway with dairy production, results can be used for wider dissemination. The farms were always selected as pairs of conventional and organic farms, preferably located in the same valley, alternatively in comparable climatic and soil conditions, and being similar in regard to farmland area and number of cows.

6.2.1 Farm production – milk and meat gain

Producing food is a main goal for dairy farming, therefore we decided to measure the production in terms of its contribution to human nutrition. Thus the production of milk and meat was measured as amount of nitrogen [kg N] for human consumption, investigating the utilisation of nitrogen, and as metabolizable energy [MJ], investigating the utilisation of primary energy. Using the average of three years reduced the influence of weather conditions on plant yield and variations in milk and meat production.

The nitrogen and energy contents of meat for human consumption was calculated on carcass weight. Thus we did not take into consideration nitrogen in the residues of slaughtered animals, despite e.g. skins are an important product. The share of the carcass-weight in regard to the liveweight reflects the prosperity of a society (Schlumpf, 2009). Taking the nitrogen of the entire animal into account, the amount of produced nitrogen would be about doubled compared to nitrogen in the carcass weight. In contrast to many other studies, the calculations are not based on weight of animals sold. The reason for this decision was that some of the farmers planned to increase milk production and thus the number of dairy cows. So they did not sell as many heifers as they otherwise had done, which in turn would have had an impact on the measured production.

For milk production we used the sum of milk delivered to dairy and private consumption (including direct sale from farm). The highest rate of private consumption and direct sale from farm was 800 litres per year and farm, and thus of little importance regarding the amount of milk delivered. If we had used milk yield from the entire herd, the amount of milk production would have been about 10 % higher for both conventional and organic farms. Some conventional farms with a milk yield above 8000 kg ECM had a delivery below 90 % of the total herd yield. This indicates that milk was not delivered due to diseases or medical treatment. Giving milk to a calf only requires about 500 kg milk, corresponding to 6 % of the annual milk yield. Using the entire milk yield from the records as product would result in a better utilisation of the investigated inputs.

Also, the decision to use metabolizable energy to human nutrition and not gross energy of milk and meat had an influence on the results obtained. While a kg of Norwegian full-cream milk with 3.9 % fat and 3.3 % protein has a metabolizable energy content of 2.78 MJ kg^{-1} (Norwegian Food Safety Authority, 2015), the gross energy would be 3.24 MJ kg^{-1} (McDonald et al., 2010). Calculating energy intensities on gross energy would reduce the intensities by 14 % in regard to the energy intensities presented in this thesis, while the intensities per 2.78 MJ metabolizable energy (corresponding to the metabolizable amount of one litre of milk) would not be affected.

In this study we compared the amount of milk under the assumption that milk from different farms with different feed compositions and milk yields is comparable, when taking into account the different amounts of fat, protein and lactose, using the formula by Sjaunja et al. (1991). But based on the work of Kusche (2015), the milk production intensity of the dairy farm influences milk quality on conventional and organic farms. He found a negative influence on the milk quality from higher intensity, less grazing, higher share of concentrates and more maize silage in the feed ration under conditions in Germany. Steinshamn (2010) found that a higher share of clover in diets for dairy cows resulted in milk containing more substances with health benefits (e.g. poly-unsaturated fatty acids and phytoestrogens).

6.2.2 Comparing and contrasting important results

Some inputs do only influence either nitrogen or energy calculations. Fixation of atmospheric nitrogen by clover can have an important impact on nitrogen budgets and nitrogen intensities, but since only energy from solar radiation is needed, clover is no part of the energy analysis in this study. On the other hand, machinery and buildings can contribute with an important share to the overall energy use, while they do not affect nitrogen calculations.

Some inputs may have larger impact on the nitrogen use than on the energy use, and vice versa. N-fertilisers, for example, contribute on average to 14 % of the entire energy input on conventional farms, while they contribute to 43 % of the entire nitrogen input of the same farms.

6.2.2.1 Nitrogen and energy intensity

The organic dairy farms in this study were found to produce nitrogen for human consumption and metabolizable energy in milk and meat with significantly lower nitrogen and energy intensities than conventional farms. In regard of these inputs, it can be concluded that organic production contributes to more sustainable farming systems, as also stated in the report by the Research Council of Norway (Research Council of Norway, 2005). More interesting than the finding that organic farms produce with lower intensities than conventional farms, is the high variation found within each of the two groups. What are the reasons for these differences? Should different strategies be chosen on conventional and organic dairy farms to improve the utilisation of inputs?

On conventional farms, the N-intensity on purchased inputs varied from 3.5 to 7.3 and the energy intensity on all inputs, including in addition N-fixation, atmospheric deposition and N-surplus on off-farm area, from 2.0 to 3.3. There were two conventional farms performing better than the others in this group, both in regard of nitrogen and energy intensity. These two farms were characterised by a lower input of concentrates and N-fertiliser (kg N/ha DF) than average of the group of conventional farms. On these farms, feed was utilised by cows with high milk yields in an efficient way. Low amounts of N-fertiliser and good agronomy may explain why these farms had a high share of clover (Enriquez-Hidalgo et al., 2015). These two farms had lower amount of energy embodied in machinery per hectare than the average of conventional farms in this study. One farm had nearly 50 % higher values for embodied energy in the barn per hectare than average, but compensated for this with the highest milk yield per cow in the entire study. The conventional farms that had the highest N-intensities had a near-average N-fertiliser use per area, but due to a low production per area and milk yield below average, the contribution of N-fertiliser to N-intensity on purchase was about 50 % above the average of conventional farms. These farms had also a higher contribution from embodied energy to their energy intensity on all inputs. Since conventional farms needed an average of 5.7 kg N from purchased inputs to produce 1 kg N in milk and meat, an increase in purchased N leads on average to an increased N-surplus per area (Fig. 2.2).

For the conventional farms it is important to underline that the production per area increased with increasing input (Fig. 2.2 and 4.2), measured as nitrogen or energy, but for the intensities, higher milk yields were more important for conventional farms than a high production per area.

On organic farms, the N-intensity on purchase varied from 1.9 to 4.2 and the energy intensity on all inputs from 1.6 to 2.9. One farm performed best both in regard of nitrogen and energy intensity. This farm was characterised by a lower contribution from concentrates and bought roughages to the N-intensity than the average of the group, having cows with milk yields of 1000 kg per cow and year above average of the organic farms. Since the amount of embodied energy for machinery and buildings per hectare was lower than average, this farm also produced with the lowest energy intensity of the organic farms. The two organic farms with highest N-intensity on purchase had a higher contribution from the sum of concentrates and imported roughages than the other organic farms, and imported in addition the highest amount of N by slurry or organic fertiliser among organic farms. One of these two farms also had a slightly higher contribution to the energy intensity from machinery and buildings than average for organic farms, which placed this farm as the organic farm with the second highest energy intensity on all inputs. The organic farm with the highest energy intensity had the lowest milk yield per cow and nearly double the contribution from embodied energy for machinery and buildings to the energy intensity on all inputs than the average of the organic farms. When only energy intensity on purchase was included, the energy intensity for this farm was comparable with the average for all organic farms.

The inclusion of nitrogen fixated by clover, increases the nitrogen intensity for all nitrogen input (nI_{all}). The nitrogen intensity (N_{iDS}) increases with the share of clover and indicates a higher nitrogen input, but nitrogen fixated by clover has the advantage that no fossil energy is required. Thus, nitrogen fixation has no impact on the energy intensity and can reduce the use of other nitrogen sources, which need energy to be produced.

6.2.2.2 Agricultural area and free rangeland

Dairy production is linked to agricultural area, and an important share of the nutrients circulate from the dairy farm area as winter fodder to the dairy herd in the barn and then as farmyard manure back to the soil. Well-adapted fertilisation contributes to increasing soil life and plant growth, but a surplus, especially of nitrogen, can result in runoff from the dairy farm area. The nitrogen surplus as a result from the calculated nitrogen balance is a good indicator for the leaching potential and local pollution (Kukreja and Meredith, 2011). The N-surplus on purchase of 192 ± 58 kg N ha^{-1} found on average for the conventional farms was high and shows a high fertilisation level, as also found by Stålnakke et al. (2014). Such high nutrient surpluses are not sustainable in the long-term, when the effects shift from local to global dimensions (Oenema et al., 2003). The N-surplus on organic farms averaged 42 ± 18 kg N ha^{-1}.

While an increased N-input from purchase increased the production of N in milk and meat gain, N-fertiliser was found to be positively correlated with the N-surplus on conventional farms. Surprisingly, no significant correlation between the use of N-fertiliser and dry matter yield on dairy farm area was found, thus indicating that it should be possible to reduce the use of N-fertiliser on many conventional farms without reducing plant production.

Our findings for land occupation (area intensity) are a bit higher for the conventional dairy farms in this study than found by Cederberg and Flysjö (2004), but their values for conventional farms with medium intensity and organic farms are close to the lower values we found for conventional and organic farms. A lower area demand in Sweden is reasonable since Cederberg and Flysjö underline that the farms in their study were located in an area with favourable conditions for milk production. Still higher yields than in Scandinavia can be expected in the Netherlands, where Boer et al. (2004) found that on an organic farm only 1.6 m^2 land were required per kg fat and protein corrected milk. The organic farms in this study required 2.7 to 4.3 m^2 land per litre milk, which is comparable with the results from Cederberg and Mattsson (2000) in regard of organic farms. The organic farms with the lowest area demand among the group of organic farms in this study and may indicate the potential of a reduced area demand for organic production. For the development of organic agriculture it is important to focus on how yields can be increased without increasing nitrogen and energy intensities.

It is not only important how much area is needed for the production of milk and meat, but also if that land would be suitable for other production. The part of the milk and meat production using surface-cultivated, native grassland and free rangeland does not compete with alternative production of human food (Schader et al., 2015). On the fully cultivated areas in the coastal region of Norway, a production of human food would be possible but not economically feasible due to the present economic conditions. It can be expected that it would be possible to grow food on most area where the different ingredients for concentrates are grown. As proposed by Schader (2015), a dairy production with less use of concentrates should be strived for.

To analyse the importance of off-farm area, different nitrogen and energy intensities were calculated, where the production of milk and meat gain on off-farm area was excluded. These intensities indicated on average only little contribution from free-rangeland in regard to feed production on other areas, while it can be important for some farms. One reason for this small effect is the calculation from the contribution from free-rangeland. For feed production on dairy- and off-farm area all different nitrogen and energy inputs from lower trophic levels were included in the calculations. On free rangeland, we only included produced milk and weight gain, which are from a higher trophic level than e.g. manure and feed. Because there is no active cultivation on free rangeland, no nitrogen or energy inputs were included. The contribution from free rangeland was important on smaller farms with long grazing periods on free rangeland. Thus the effect from free rangeland is underestimated by calculating average numbers for the groups of conventional and organic farms.

Calculating the share of energy uptake on free-rangeland to overall feed demand can give a better impression of the importance. While free-rangeland contributed an average of 5.9 % on conventional and 8.1 % on organic farms, the share was 23 % on one organic farm with extensive use of free-rangeland for all animals nearly the entire growing season. Without utilizing free rangeland, this farm would have to increase its own dairy farm area by 73 %. For the average conventional and organic farms, the dairy farm area would have to be increased by 21 % and 29 %, respectively. These figures demonstrate the importance of free-rangeland for the dairy farms in this region. Where available, expanding the use of free-rangeland could be a solution for using less agricultural area for milk and meat production, contributing to higher food production on existing agricultural area to feed an increasing global population (Rockström et al., 2009).

We found in our study that more area is needed for organic production. To be a sustainable solution, it is important for organic dairy farming to mainly utilise areas that do not compete with food production for direct human consumption, use by-products from food production or grassland as a necessary part of a crop rotation, and work for increasing yields per area already in use without negative side effects. But the need for agricultural area alone is not a sufficient indicator for worldwide food production. Based on UNCTAD (2014), the worldwide food production in 2013 would have been sufficient to feed 12-14 billion people, while *"one billion people chronically suffer from starvation and another billion are malnourished"* on the one side and worldwide about 1.6 million adults above 15 years were estimated to be obese in 2005 on the other side (Low and Yap, 2009). UNCTAD highlight as the main problem for starvation prevailing poverty and access to food. In recent years the focus on food waste has increased (e.g. Brul, 2012; Gunders, 2012) and it is estimated that worldwide about one third of the food produced for human consumption gets lost or wasted (Cederberg et al., 2011a). Wasted food is not only a reason for lack of food and resulting starvation, it means also that resources are used in vain and cause the emission of greenhouse gases. Also in Norway, food waste has been analysed (Hanssen and Møller, 2014) and estimated to be 25 % of sold food, with private consumers causing 70 % of the food waste. Reduced food waste alone could thus compensate for the lower yields on organic farms in Norway. So both consumers and agriculture have their share of responsibility, with mode of food production having a higher impact on the amount of reactive nitrogen in the environment than the food consumption (Leach et al., 2012).

6.2.2.3 Embodied energy in agricultural buildings and machinery

The amount of nitrogen used to produce buildings and machinery is negligible and thus buildings and machinery are not part of the analysis of nitrogen utilisation. But we found that the embodied energy in buildings and machinery can have an important contribution to the overall consumption of primary energy on dairy farms. For embodied energy in all agricultural buildings, we found a variation from 6 % to 32 % in relation to overall energy use on the farm, which was in line with the findings by Erzinger (2004), while machinery contributed with additional 8 % to 27 %. But the sum of embodied energy in buildings and machinery did not contribute more than maximum 43 % of the entire energy used. This figure was found on two organic farms with below-average milk yields.

While the amount of embodied energy in buildings and machinery is difficult to reduce in the short run, good maintenance can increase their usage beyond the expected lifetime, which would result in lower yearly amounts of embodied energy. But also an increased production with the existing buildings and machinery would reduce energy intensities. Thus, some of the organic farms are hampered by former production, having built their barns before they converted to organic farming. Due to lower harvested yields and less milk production due to decreased use of concentrates, the amount of embodied energy has to be divided on less milk and thus results in a higher contribution from buildings on the intensities. This effect was particularly obvious on organic farms with low milk yields (Fig. 4.3 and 4.4b).

For the amount of embodied energy in barns, two important effects can be emphasized. First, it is important how much energy is embodied in the barn per cow-place. The second effect is the production per cow.

Analysing which variables determine the amount of embodied energy, we found that nearly 90 % of the variation could be explained by the three factors; a) square meter ground-floor in all barns per cow-place, b) square meter walls in all barns per cow-place and c) square meter concrete walls with insulation or barn-walls in new materials in all barns per cow-place (Table 3.6). Although none of the barns analysed was built with any advice on how to build with less embodied energy, we found a variation from 750 to 5,250 MJ per cow-place embodied in the envelope of the barns. These differences demonstrate that there are potentials to reduce the amount of embodied energy, when new barns are being designed and the new knowledge on how to construct agricultural buildings with less embodied energy is implemented.

The influence of the milk yield per cow is easy to understand, using a theoretical high milk yield of 9000 kg/cow and a low yield of 3000 kg/cow. If these cows were placed in the same barn, the higher yielding cow would have just 1/3 of the amount of embodied energy per litre of milk from the barn as the cow yielding 3000 kg milk. This simple calculation underlines the importance of building barns with lower amounts of embodied energy when milk yields are low, which more often is the case in organic farming, and where in addition the regulation requires more area per animal to ensure animal welfare. This effect may also help to explain the high share of embodied energy on the organic farms with low milk yield and a lower energy intensity on all inputs for conventional farms with higher yielding cows (Fig. 4.4 b).

Also for machinery, the production intensity has an important influence. Soil cultivation such as ploughing needs the same energy independent of plant yield. Thus, it could be expected that farms with lower yields had a higher amount of embodied energy than those with higher yields.

Despite recurring justifications for why embodied energy from buildings is not included in LCA studies (Harris and Narayanaswamy, 2009), I think that the main reason for an exclusion is often the actual time needed to perform such analyses. Even if little can be done to reduce the amount of embodied energy from machinery and buildings in the medium term (Lebacq et al., 2013), information on the actual status and how to reduce embodied energy is crucial, especially when farmers consider investing in new machinery or are planning to build new buildings or alternatively expand existing ones. Such decisions will have an important influence on the total energy use on the farm for many years.

6.2.2.4 Farm size

Larger farms having more area and more dairy cows can be expected to use technical equipment more efficiently and thus produce with lower cost and less energy than smaller farms. In contrast to this, we found for conventional farms that increasing area was positively correlated with more tractorweight per farm area and increased energy intensity calculated on purchase and technical equipment, and calculated on all input. On organic farms, a higher share of the energy uptake by cattle was from grazing than on conventional farms, but this share decreased with increasing farm size. And while the share of grazing decreased, the larger organic farms used more concentrates for cattle and stored less silage in towers, which resulted in a higher energy use due to silage foil per area than on smaller farms.

Albeit organic farms had lower energy intensities on purchase and lower nitrogen input from purchase on average than conventional farms, this benefit was reduced when farm area increased. Based on these findings, the organic farms with less area contribute more to environmental goods than conventional farms and organic farms with more area. This coincides with the statement in a White Paper from the Norwegian Ministry of Agriculture (1999). In terms of environmental performance, the smaller organic farms seem comparable to the group of alpine dairy farms described by Penati et al. (2011). They found that farms with low stocking density, low production intensity, high feed self-sufficiency, and large land availability in the valley, were more efficient in utilizing nitrogen.

6.2.2.5 Intensities as tool for farmers, extension service and politicians

When the legislation on fertilizing planning was introduced in 1998 (Ministry of Agriculture and Food, 2002), it was perceived by many farmers as an extra duty. But many discovered that fertilising schemes could be helpful in increasing the utilisation of nutrients and reducing costs for buying fertiliser.

Starting the EnviroMilk project and presenting the first results on nitrogen and energy utilisation to the participating farmers showed that nitrogen balances, nitrogen and energy flow diagrams for farms and intensities where quite interesting, both for determining the on-farm status and looking for solutions to improve utilisation of inputs. Since such calculations had not been used before, it was much easier for the farmers to understand the situation on their own farm when farm data were compared to other farms. Some of them started wondering why they used so much nitrogen, when others were achieving high yields with a much lower input, not being aware of the sum of nitrogen from fertilisers, concentrates, manure and nitrogen fixation by clover on their own farm despite the fertilising plans they used. The results showed that most farmers used a higher share of concentrates than they were aware of. Others told about plans to build a new barn, but that they could not get any information on the effect of different solutions on embodied energy and how to find solutions to reduce embodied energy.

When communicating the responsibility to improve the utilisation of nutrients and energy, it is important to understand the situation of the farmers, who are forced to farm profitably, and their goals. Organic grain farmers in Norway were found to have sustainable and environment-friendly farming as their main goal for farming (Koesling et al., 2004), while conventional farmers had a reliable and stable income as their top priority. Thus it is an advantage that improving nitrogen, energy and area intensity has no negative effect on economic intensity as shown in chapter 5.3.

Figures and tables similar to those in this thesis have been used in meetings with farmers, advisers and politicians. For advisers and politicians, the variation in intensities was of special interest. It would be reasonable to use existing data on fertilising plans, often prepared by the extension service, and supplement them with accounting data as a tool to help farmers improve intensities. Our results could be used as a first benchmarking for other dairy farms.

For farmers it should be highly recommended to compare the use of concentrates used according to feeding schemes with the actual amount of concentrates bought. When these two quantities differ, it should be analysed if there is an overconsumption, which would result in increased cost, or if it is required for the milk and meat production. For framing agricultural policy, it could be recommended to design grants to support improve nutrient and energy utilisation, especially since there is a goal to increase production in Norway in a sustainable way (Minister of Agriculture and Food, 2011).

6.3 General conclusions

The ten conventional and ten organic dairy farms showed high variations in nitrogen and energy utilisation. Assuming that these farms represent much of the variation found in dairy farming elsewhere in Norway, it can be assumed that it is possible for many farms to reduce nitrogen and energy input without reducing production or to increase production using the same amount of input. Both strategies would strengthen the environmental sustainability of dairy farming. The possible strategies found for conventional and organic farms differed.

The organic farms produced on average with lower nitrogen and energy intensities on purchased inputs than the conventional ones. But the analyses showed also high variations within both modes of production, with the most efficient conventional farms producing with lower intensities than the organic farm with highest values. This demonstrates two things. First, that it is not given that nutrient and energy utilisation on an organic farm is more efficient than on a conventional farm just because the farm is “organic”. Second, that for most conventional and some organic farms, there are possibilities for improving nitrogen and energy utilisation.

To utilize the potential for improvements I would recommend to expand compulsory fertilising schemes on farms to include nutrient balances and to utilise the expertise of the agricultural expansion service to use data from other farms as bench marking. Such comparisons are more interesting for farmers when economic results are also included, thus enabling the possible increase of farm income, while nitrogen utilisation is improved.

Albeit IFOAM mentions the importance of developing organic farming to be more energy efficient in terms of both area and product basis (Kukreja and Meredith, 2011), so far information on energy consumption for food production is difficult to obtain for farmers. The project has shown that farmers are interested in the topic. A possibility to provide more information to farmers could be a further expansion of fertilising schemes. More schemes would require more work for the farmers, which should result somehow in a payoff to be accepted. As a solution, a better utilisation of nitrogen and energy could be linked to subsidies and used in marketing local products and environmental farming, which is utilised in other countries (Schaffner and Packeiser, 2008).

The analyses highlight two hot spots: N-fertiliser in regard of utilisation of nitrogen and machinery and buildings in regard of energy.

6.3.1 Nitrogen fertiliser

The conclusion that conventional farms can decrease energy and nitrogen intensity is based on the situation found on the farms in this study, and it should be taken into account that other solutions for reducing intensities exist than used by the farmers in this study. One obvious solution is the reduction of the use of N-fertiliser where there are high N-surpluses. This is supported by the finding that higher fertilisation levels are not correlated with higher yields. Less use of N-fertiliser would reduce both nitrogen and energy intensities. It could be a solution to use most of the N-fertiliser at the beginning of the growing season when the soils are still cold and thus the mineralisation rates are low. Later in the growing season there should be enough nitrogen available for the plants, and no or low levels of N-fertiliser would be sufficient, based on the nitrogen balances calculated. A good example in this study is the conventional farm that had a much lower N-fertilising level than average, and in spite of this had higher yields and higher milk and meat production per area than the average of conventional farms. By this, the intensity levels for nitrogen and energy were low on this farm.

Finding an explanation for the high N-fertilising levels was not a goal of the study, but it seems to be important to understand the reasoning underlying this behaviour (Vatn et al., 1999). Especially since this is not the first study finding that Norwegian farmers use more N-fertiliser than scientists and farm advisers recommend (Riley et al., 2012).

Mainly, there are two arguments for a higher N-application level than recommended. The first is the argument that a higher N-supply is used to guarantee that high yield potentials are utilised (Sheriff, 2005; Øgaard, 2014), and the other is the argument that it is economically favourable to use more fertiliser when the relative cost of fertilisers to milk and meat is low (Mihailescu et al., 2015). In Norway, the producer prices for milk and meat are higher, while the price for fertiliser is comparable to the level in other countries. Keeping the price of fertiliser low was also a goal for politicians (Ministry of Agriculture and Food, 2008), and the argumentation used indicates that lower prices for fertiliser are considered as a way to increase farmers' income. But it should be considered that lower prices for fertiliser and high product prices result in a higher fertilising level (Koesling, 2005) and may be one reason for the rather modest reduction of fertilizer consumption in Norway (Bechmann et al. 2014).

6.3.2 Buildings and machinery

Due to their amount of embodied energy, buildings and machinery contributed with an important share of the overall energy consumption (35 % as average for all farms; 16 % buildings, 19 % machinery). Due to a lower production per cow, area and barn place, their contribution was higher for organic than for conventional farms (average organic: 20 % buildings, 23 % machinery). These figures can be reduced (also by conventional farms) if existing machinery and buildings are maintained and can thus be used longer than the expected lifetime, or if production with the buildings and machinery on farm is increased. Despite the higher share of energy use by buildings and machinery, it is important to keep in mind that the organic farms produce nutritional energy on average with less energy than the conventional ones.

Lebacq et al. (2013, page 323) report that in herbivore livestock farming 20 % of the energy used relates to machinery and buildings, and that a farmer has little leeway to change this consumption. Under Norwegian conditions, this figure is too low. Farmers can reduce the amount of embodied energy in new buildings if they calculate the amount of embodied energy and choose materials with low amounts of embodied energy and a design demanding less material. When a new building is planned, updating and renovation of the existing building should be considered as an alternative. However, if a new building is necessary, an energy efficient barn should be planned (Koesling et al., 2015). When buying a new tractor, it should be avoided to buy a bigger tractor than necessary. The fact that the tractor-weight per farm area was only correlated to the intensity for all energy and not to the use of diesel can indicate that there was an over-mechanisation, or that diesel was more efficiently used when the tractor-weight per farm area was higher.

7 Summary

To improve environmental sustainability it is important that all sectors in a society contribute to improving the utilization of inputs as energy and nutrients. In Norway, dairy farming contributes with an important share to the added value from the agricultural sector, although there is little information available about utilization of energy and nitrogen (N). Many results on sustainability have been published on dairy farming. However, due to Norway's Nordic climatic conditions, mountainous and rugged topography and an agricultural policy that can design its own prices and subsidies, results from other countries are hardly representative for Norwegian conditions. To bridge this gap, the objective of this study was to analyse if the utilisation of nitrogen and energy in dairy farming in Norway can be improved to strengthen its environmental sustainability.

Data were collected from 2010 to 2012 on 10 conventional and 10 organic farms in a region in central Norway with dairy farming as the main enterprise. The farms varied in area, number of dairy cows and milk yield. For nitrogen, a farm gate balance was applied and supplemented with nitrogen fixation by clover and atmospheric N-deposition. The total farm area was broken down into three categories: dairy farm area utilized directly by the farm, off-farm area needed to produce imported roughages and concentrates, and free rangeland that only can be used for grazing.

To analyse the utilization of nitrogen and energy, comparable indicators and two functional units are introduced. The use of inputs is analysed by a lifecycle assessment from cradle to farm gate. The functional units for nitrogen and energy are, respectively, 1 kg N for human consumption, with N as important component of protein, and 1 MJ of metabolizable energy in delivered milk and meat gain of the cattle herd. Thus, the input of nitrogen and energy can be measured in the same unit as the corresponding functional unit, and utilisation can be expressed as intensities. Intensities are the amount of input needed to produce one functional unit and are dimensionless. For the farm they are calculated by dividing the input (measured as kg N or MJ embodied energy needed for production) by the output (measured respectively as kg N or MJ metabolizable energy in delivered milk and meat gain). Different intensities are calculated, depending on which inputs are included, e.g. including nitrogen fixated by clover or not or embodied energy from buildings or not. Embodied energy is the sum of all fossil and renewable energy, required to produce an input. Man-power and solar radiation are not included.

The N-inputs per functional unit on all 20 farms are presented in a bar graph, visualising the contribution of the inputs to the N-intensities. N-intensities on organic dairy farms vary between 1.9 and 4.2, compared to a variation on conventional farms ranging from 3.5 to 7.3. A linear regression demonstrates that the N-intensity on purchased N and the off-farm N-surplus on conventional farms decreases with increasing milk yield, while the intensities on organic farms were lower, regardless of whether milk yields were high or low. Of an increased N-input on purchase, on average only 11 % is utilised as output, resulting in increased nitrogen surplus per area. Different variables are tested for correlation with their influence on the N-intensities. A model for all 20 farms is developed, showing that the N-intensity on purchased inputs decreases with an increasing feed-derived share of the entire N-import by purchase and with decreasing N-fertiliser use per area. It is concluded that N-intensities are suitable for quantifying the utilization of N and the share of different inputs to the N-intensities and easily comparing farms.

Enabling the inclusion of embodied energy from agricultural buildings with a lower workload than a mass material calculation requires, the building construction approach is introduced. The agricultural buildings on all farms were registered and the material layers of the key building elements was described. The area of each building element was multiplied by the amount of embodied energy per square meter and the results for all elements summed up for each building.

On average for the 20 barns, the value of embodied energy in the envelope per cow-place and year was about 2,700 MJ, varying from 750 to 3,400 MJ. The results show that square meter area per cow-place, use of concrete in walls and insulation in concrete walls are the variables that contribute significantly to increasing the amount of embodied energy. It is highlighted that by choosing a design that requires less material and materials with a low amount of embodied energy, the amount of embodied energy in buildings can be significantly reduced.

Furthermore, the variation in energy utilisation and possible improvements are analysed. Comparable to nitrogen input, an increasing production of metabolizable energy per hectare can be explained by an increased input of embodied energy from all inputs, with a utilisation of nearly 40 % on conventional and nearly 50 % on organic farms. Energy intensities calculated were significantly lower on organic than on conventional farms.

The contribution of embodied energy from the different inputs to the energy intensities is shown for all 20 farms. Machinery and buildings are found to contribute with an average of 19 % on the conventional farms and 29 % on the organic farms to energy intensity on all inputs, with a variation of 15 % to 43 % for all 20 farms. Calculated on all inputs, the energy intensities on conventional farms varied from 2.1 to 3.3 and on organic farms from 1.6 to 2.9. On conventional farms, the energy intensities decreased with increasing milk yield, while organic farms produced without a significant influence from milk yield. These findings are comparable to this study’s finding on the influence on milk yield on nitrogen intensity. On organic farms, there was a bigger influence from machinery and buildings on energy intensity than on conventional farms, especially on those organic farms with low milk yields.

The influence of different variables on the energy intensities is analysed. This is done separately for conventional and organic farms because different variables are found to be important both in regard of conventional or organic production, and depending on if only energy from purchased inputs or also energy embodied in infrastructure is included. The energy intensity on conventional farms is positively correlated to tractorweight per area and nitrogen intensity on purchased inputs. On organic farms the energy intensity is positively correlated with the ground-floor area per cow in the barn and negatively correlated with liveweight per cow and share of nitrogen fixated by clover of total nitrogen input by purchase. Due to the important contribution from machinery and buildings to the overall energy consumption in dairy farming it is highly recommended to include them in energy-analyses and to find solutions to improve their utilisation.

Comparing nitrogen, energy, area, and economic intensities underlines that on conventional farms, nitrogen, energy, and area intensities are positively correlated, while on organic farms only energy and area intensities are positively correlated. When looking for more environmentally sustainable solutions for dairy farming, it is an advantage that some intensities are positively correlated and not negatively correlated to the economic outcome. Among the 20 farms, three conventional and three organic farms performed better than average within their respective group in regard to all four intensities.

The organic dairy farms in this study produce milk and meat on average with lower nitrogen and energy intensities and lower nitrogen surplus per area than the studied conventional farms. Intensities are found to be superior to efficiencies since they not only display the utilisation of nitrogen and energy, but also allow displaying the share of each input. This feature is important for communicating with farmers and finding solutions aimed at reducing intensities. It is concluded that the utilisation of nitrogen and energy can be improved, and different solutions are recommend for conventional and organic farms, respectively. Presumably, the best results can be obtained by conducting farm-specific analyses for finding solutions for reduced intensities and by developing agricultural policies that support a better utilisation of nitrogen and energy in the production of milk and meat.

8 Zusammenfassung

Soll die umweltbezogene Nachhaltigkeit verbessert werden, muss in allen Wirtschaftszweigen die Ausnutzung der verwendeten Energie und Nährstoffe verbessert werden. In Norwegen trägt Milchviehhaltung zu einem großen Anteil zur Wertschöpfung des landwirtschaftlichen Sektors bei. Trotzdem gibt es kaum Informationen darüber, in welchem Grad Energie und Stickstoff (N) ausgenutzt werden. International gibt es viele Studien zur Nachhaltigkeit der Milchviehhaltung. Doch durch das nordische Klima, die Gebirge mit der zerklüfteten Landschaft und einer eigenen Agrarpolitik mit eigenen Subventionsordnungen und Preisen für landwirtschaftliche Produkte, ist kaum zu erwarten, dass Ergebnisse aus anderen Ländern repräsentativ für norwegische Bedingungen sind. Um diese Lücke zu schließen, war es Ziel dieser Arbeit, den Ausnutzungsgrad von Energie und Stickstoff zu analysieren und zu untersuchen, ob der Ausnutzungsgrad erhöht und damit die umweltbezogene Nachhaltigkeit verbessert werden kann.

Die Daten für die Studie wurden in den Kalenderjahren 2010 bis 2012 auf 10 konventionell und 10 ökologisch bewirtschafteten Betrieben erhoben, die Milchviehhaltung als Hauptwirtschaftszweig haben und in der Mitte Norwegens gelegen sind. Die Betriebe unterschieden sich in Bezug auf landwirtschaftliche Nutzfläche, Zahl der Milchkühe und Milchleistung pro Kuh. Für Stickstoff wurde eine Hoftorbilanz erstellt, die durch Stickstoffbindung durch Klee und atmosphärischer Deposition ergänzt wurden. Die Fläche der Betriebe wurde unterschieden in hofeigene Flächen, hoffremde Flächen, auf denen zugekauftes Kraft- und Raufutter angebaut wird, sowie Wildflächen und Almwiesen in den Bergen, die nur durch Beweidung genutzt werden können.

Um zu untersuchen, wie gut Stickstoff und Energie ausgenutzt werden, wurden vergleichbare Indikatoren und zwei funktionelle Einheiten eingeführt. Die Verwendung von Inputfaktoren ist mit Hilfe einer Lebenszyklusanalyse von der Wiege bis zum Hoftor untersucht worden. Die funktionellen Einheiten für Stickstoff und Energie sind 1 kg Stickstoff für die menschliche Ernährung (mit Stickstoff als wichtigem Baustein für Protein) sowie 1 MJ metabolischer Energie in der verkauften Milch und dem Fleischzuwachs. Dadurch kann der Einsatz von Stickstoff und Energie jeweils in der gleichen Einheit erfolgen, wie die der funktionellen Einheit und der Grad der Ausnutzung als Intensität dargestellt werden. Intensitäten geben die Menge des Aufwandes an, der für die Menge der funktionellen Einheit verwendet wurden und sind dimensionslos. Für einen Betrieb werden sie als Quotient mit dem Aufwand (gemessen als kg Stickstoff, beziehungsweise Energie, die zur Produktion notwendig waren) im Zähler und der produzierten Menge (gemessen als kg Stickstoff, beziehungsweise Energie in verkaufter Milch und Fleischzuwachs) im Nenner. Verschiedene Intensitäten werden berechnet, abhängig davon, welcher Aufwand mit einbezogen wird; ob zum Beispiel Stickstoffbindung durch Klee oder Graue Energie (Embodied Energy) mit einbezogen werden oder nicht. Die Graue Energie ist die Gesamtmenge an fossiler und regenerativer Energie, die zur Erstellung eines Produkts benötig wurde. Menschliche Arbeitskraft und Sonnenenergie bleiben dabei unberücksichtigt.

Die Menge an Stickstoff pro funktioneller Einheit für jeden der 20 Betriebe ist in einem Säulendiagramm dargestellt und zeigt zugleich den Anteil der unterschiedlichen Aufwendungen. Die Stickstoffintensität variiert auf ökologischen Betrieben zwischen 1,9 und 4,2, während sie auf konventionellen Betrieben zwischen 3,5 und 7,3 liegt. Durch eine lineare Regression wird gezeigt, dass die Stickstoffintensität in den verwendeten Vorleistungen auf konventionellen Betrieben bei steigender Milchleistung pro Kuh sinkt. Auf ökologisch bewirtschafteten Betrieben ist die N-Intensität grundsätzlich geringer und wird nicht durch die Milchleistung beeinflusst. Bei einem Anstieg des N-Aufwandes durch die Vorleistungen steigt im Schnitt aller Betriebe der Stickstoff in der produzierten Milch und Fleisch nur um 11 % des N-Mehraufwandes, was zu steigenden Stickstoffüberschüssen in der N-Bilanz auf der Wirtschaftsfläche führt. Unterschiedliche Variablen wurden auf ihre Korrelation zur N-Intensität untersucht. Ein statistisches Modell für alle 20 Betriebe zeigt, dass die N-Intensität durch die Vorleistungen sinkt, wenn ein größerer Anteil des Stickstoffes in den Vorleistungen von Futterstoffen stammt und wenn weniger N-Dünger pro Fläche verwendet wird. Es wird gefolgert, dass N-Intensitäten geeignet sind, die Ausnutzung von Stickstoff und den Anteil verschiedener Aufwendungen zu messen und Höfe einfach zu vergleichen.

Durch die Verwendung eines Standardbauteil bezogenen Ansatzes kann die Menge der Grauen Energie in landwirtschaftlichen Gebäuden mit weniger Arbeitsaufwand berechnet werden als mit der Berechnung aller Materialmengen (mass material calculation). Die landwirtschaftlichen Gebäude auf allen Betrieben wurden erhoben und die Materialschichten der wesentlichen Bauelemente ermittelt. Die Fläche der verschiedenen Bauelemente wurde dann mit dem Energiewert pro Quadratmeter multipliziert und alle Werte für das Gebäude summiert.

Im Durchschnitt für die 20 Betriebe, war der Werte der Grauen Energie pro Stallplatz für eine Kuh pro Jahr rund 2.700 MJ und variierte von 750 bis 3.400 MJ. Es wird gezeigt, dass die Grundfläche im Stall pro Kuh, die Verwendung von Beton in Wänden und Isolation in Betonwänden, die Variablen sind, die signifikant den Wert der Grauen Energie erhöhen. Es wird hervorgehoben, dass durch die Wahl einer Konstruktion, die weniger Material benötigt und die Verwendung von Materialien mit geringem Energieeinsatz in der Herstellung der Wert der Grauen Energie in Ställen signifikant reduziert werden kann.

Zudem werden die Ausnutzung von Energie und mögliche Verbesserungen der Energieeffizienz untersucht. Vergleichbar zum N-Aufwand, kann eine steigende Produktion metabolischer Energie pro Hektar durch einen steigenden Einsatz der Grauen Energie von allen Aufwendungen erklärt werden, wobei auf konventionellen Betrieben 40 % und auf ökologischen 50 % der aufgewandten Energie als metabolische Energie ausgenutzt werden. Die Energieintensitäten waren auf ökologischen Betrieben signifikant geringer als auf konventionellen.

Der Beitrag der Grauen Energie der einzelnen Aufwendungen zur Energieintensität wird für alle 20 Betriebe gezeigt. Maschinen und Gebäude tragen im Schnitt mit 19 % auf konventionellen Betrieben und 29 % auf ökologischen Betrieben zur gesamten Energieintensität bei, wobei der Wert von 15 % bis 43 % in der Gruppe aller 20 Betriebe schwankt. Die Energieintensität für den gesamten Aufwand variiert auf konventionellen Betrieben von 2,1 bis 3,3 und auf ökologischen Betrieben von 1,6 bis 2,9. Auf konventionellen Betrieben sinkt die Energieintensität bei steigender Milchleistung pro Kuh, während ökologische Betriebe ohne signifikanten Einfluss der Milchmenge produzieren. Diese Ergebnisse sind denen der Milchleistung auf die N-intensität vergleichbar. Auf ökologischen Betrieben, war der Einfluss von Maschinen und Gebäuden auf die Energieintensität grösser als auf konventionellen Betrieben, dieser Effekt war noch grösser auf ökologischen Betrieben mit geringer Milchleistung pro Kuh.

Der Einfluss verschiedener Variablen auf die Energieintensität wird getrennt für die konventionellen und ökologischen Betriebe untersucht, da für die beiden Wirtschaftsweisen unterschiedliche, relevante Variablen gefunden wurden. Darüber hinaus haben unterschiedliche Variablen Bedeutung, abhängig davon, ob nur die Graue Energie der Vorleistungsprodukte oder auch die Infrastruktur berücksichtigt wurden. Auf konventionellen Betrieben ist die Energieintensität positiv mit dem Traktorgewicht pro

Flächeneinheit und der Stickstoffintensität der verwendeten Vorleistungsprodukte korreliert. Auf ökologischen Betrieben ist die Energieintensität positiv mit der Grundfläche im Stall pro Kuh und negativ mit dem Lebendgewicht pro Kuh, sowie dem N-Anteil, der pro Hektar durch Klee fixiert wurde, an der Gesamtmenge an Stickstoff in den Vorleistungsprodukten korreliert. Da Maschinen und Gebäude bedeutend zum gesamten Energieverbrauch auf Milchviehbetrieben beitragen, wird nachdrücklich empfohlen, sie in Analysen zum Energieverbrauch mit einzubeziehen und dann Lösungen zur verbesserten Energieeffizienz zu finden.

Ein Vergleich der Intensität von Stickstoff, Energie, Arbeit und Wirtschaftlichkeit zeigt, dass auf konventionellen Betrieben die Stickstoff-, Energie- und Arbeitsintensität positiv miteinander korreliert sind, währen auf ökologischen Betrieben nur Energie- und Arbeitsintensität positiv miteinander korreliert sind. Auf der Suche nach Lösungen für eine verbesserte umweltbezogene Nachhaltigkeit für die Milchviehhaltung, mag es ein Vorteil sein, dass die Intensitäten positiv und nicht negativ miteinander korreliert sind und es auch keine negative Korrelation zur Wirtschaftlichkeit gibt. Unter den 20 Betrieben gab es jeweils drei konventionelle und drei ökologische, die in Bezug auf alle vier Intensitäten besser als der Durchschnitt ihrer Kollegen produzierten.

Die ökologisch wirtschaftenden Milchviehbetriebe in dieser Studie produzieren im Durchschnitt mit geringeren Stickstoff- und Energieintensitäten und geringerem Stickstoffüberschuss pro Fläche als die untersuchten konventionellen Betriebe. Intensitäten haben sich als vorteilhaft gegenüber Effizienzen erwiesen, da sie nicht nur die Ausnutzung von Stickstoff und Energie zeigen, sondern es auch erlauben, den Anteil der verschiedenen Aufwendungen zu zeigen. Dieser Möglichkeit kommt besondere Bedeutung zu, wenn die Ergebnisse Landwirten vermittelt und Lösungen für reduzierte Intensitäten gesucht werden sollen.

Die Schlussfolgerung dieser Arbeit ist, dass die Ausnutzung von Stickstoff und Energie verbessert werden kann und verschiedene Lösungen für konventionelle und ökologische Betriebe empfohlen werden sollten. Gute Maßnahmen können nur gefunden werden, wenn Höfe individuell betrachtet werden und die Landwirtschaftspolitik so entwickelt wird, dass eine bessere Ausnutzung von Stickstoff und Energie bei der Produktion von Milch und Fleisch unterstützt wird.

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