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Variations of energy intensities and potential for improvements in energy utilisation on conventional and organic Norwegian dairy farms

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A B S T R A C T

Due to the limited resources of fossil fuels and the need to mitigate climate change, energy utilisation 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, to examine 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 to 2012 were used to calculate the amount of embodied energy as the sum of primary energy used for production of inputs from cradle-to-farm gates using a life cycle assessment (LCA) approach. Energy intensities of dairy farms were used to show the amount of embodied energy needed to produce the inputs per metabolizable energy in the output. Energy intensities allow to easily point out the contribution of different inputs. The results showed that organic farms produced milk and meat with lower energy intensities on average than the conventional ones. On conventional farms, the energy intensity on all inputs was 2.6 ± 0.4 (MJ MJ^{-1}) and on organic farms it was significantly lower at 2.1 ± 0.3 (MJ MJ^{-1}). 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.

For conventional and organic dairy farms, different strategies are recommend to reduce the energy intensity on all inputs. Conventional farms can reduce energy intensity by reducing the tractor weight and on most of them, it should be possible to reduce the use of nitrogen fertilisers without reducing yields. On organic dairy farms, energy intensity can be reduced by reducing embodied energy in barns and increasing yields. The embodied energy in existing barns can be reduced by a higher milk production per cow and by a longer use of the barns than the estimated lifetime. In the long run, new barns should be built with a lower amount of embodied energy.

The high variation of energy intensity on all inputs from 1.6 to 3.3 (MJ MJ^{-1}) (corresponding to the energy use of 4.5–9.3 MJ kg^{-1} milk) found on the 20 farms shows a potential for producing milk and meat with lower energy intensity on many farms. Based on the results, separate recommendations were provided for conventional and organic farms for reducing energy intensity.

1. Introduction

The green revolution was the main cause for the significant increase in food production. Inputs such as fertilisers, pesticides, and farm machinery replaced human- and animal-power and contributed to the production increase. However, this development resulted in a high dependency on external energy. This dependency received its first public attention during the oil crisis of the early

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1970s, and Pimentel et al. (1973) published one of the first studies on energy intensity in agriculture. Since the energy intensity in intensive livestock is much higher than in agricultural crops (Pelletier et al., 2011), it is important to analyse the intensity and look for possible improvements for its reduction. The amount of all non-renewable and renewable energy resources from cradle-to-gate except manpower and solar radiation, used to produce milk on dairy farms has been calculated in many European studies.

So far, studies on energy utilisation have mainly focussed on the amount of embodied energy used directly or indirectly by purchased inputs in dairy farming, not taking into account the contribution from machinery and buildings. Only some studied both conventional and organic farming, and they presented only the average values for each mode of production. Using average values hides the variation found in energy utilisation on commercial farms and does not allow to see the performance of the best farms for the two modes of production. The use of individual farm data allows to analyse were the strengths and weaknesses of the different production modes in regard of energy utilisation are, and were to focus for improving the energy utilisation.

On conventional dairy farms, the energy needed to produce one litre of milk, without considering the energy needs of buildings and machinery, was found to be 2.4 MJ kg^{-1} ECM (energy-corrected milk) (Upton et al., 2013) in Ireland and 3.7 MJ kg^{-1} ECM (Cederberg et al., 2007) in Sweden.

Some studies examined organic and conventional farms (e.g. Cederberg and Flysjö, 2004; Thomassen et al., 2008). They always found lower energy demand for producing milk on organic farms than on conventional. Thomassen et al. (2008) found this not only for their own study in the Netherlands, but also for studies from Sweden and Germany. The energy demand by purchased inputs in the different studies varied from 2.6 to 5.0 MJ kg^{-1} ECM for conventional farms and from 1.2 to 3.1 MJ kg^{-1} ECM for organic farms.

Despite that the share of embodied energy in buildings can be substantial and has been reported to be up to 32% (Rossier and Gaillard, 2004) of the total energy consumption on commercial dairy farms in Switzerland, most of the studies reviewed by Yan et al. (2011) and Baldini et al. (2017) did not include energy use linked to machinery, barns, and other agricultural buildings.

European studies that include all energy input were from Switzerland and Germany. Only Rossier and Gaillard (2004) presented the results for each farm from their study in Switzerland and included embodied energy by purchased inputs, machinery and buildings. The energy use for mixed farms with dairy production ranged from 3.7 to 12.3 MJ kg^{-1} ECM.

Taking account for all embodied energy on dairy farms, Erzinger et al. (2004) found that the energy demand varied from 4.1 to 6.0 MJ kg^{-1} ECM. Hersener et al. (2011) found lower values for dairy farms placed in valleys (4.8 MJ kg^{-1} ECM) than for farms placed in the mountains (6.0 MJ kg^{-1} ECM).

Only Refsgaard et al. (1998) studied the energy from purchase, machinery and buildings with data on conventional and organic milk production. They found, on dairy farms with 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 farms.

Because there are very few results including all energy use and comparing conventional and organic dairy farms, more investigations are needed.

In Norway, dairy farming is an important part of agriculture with 31% of all farms having cattle and two third of them having dairy production in 2015 (Statistics Norway, 2016). Due to long winters, the vegetation period is short and cattle can only graze three to four month. To avoid high amounts of imported fodder to the farm, a part of the fodder produced in the short vegetation period has to be stored for long winters. Barns in Norway need high energy input, because of the embodied energy for insulation and heating in milking parlours. Despite the studies in other Scandinavian countries, energy intensities on commercial dairy farms of both modes, conventional and organic, have not been addressed under Norwegian conditions yet.

The objective of this study on dairy farms was to determine 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 embodied energy on different farms producing milk and meat. While efficiency describe the ratio of outputs to inputs (Godinot et al., 2015), intensities are the inverse of efficiency, describing the ration of inputs to outputs. Energy intensities have been used for example by Bullard and Herendeen (1975). Intensities make it possible to assess the influence of each input individually. In this study, intensities are defined as 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 as the sum of primary energy (from regenerative and fossil resources) per dairy farm hectare of inputs in the nominator and the amount of produced metabolizable energy from milk and meat per dairy farm hectare in the denominator.

Moitzi et al. (2010) used energy intensities with a focus on the concentrate level in dairy production in Austria. Kraatz et al. (2009) analysed the effect of different feedstuffs and of all inputs (Kraatz, 2012) on the energy intensity in dairy farming. Energy intensities have also been used in crop production to find improvements for fertilisation (Hülsbergen et al., 2001).

In the literature, different energy intensities were used as indicators of resource use on farms. Energy intensities as used in this study have been named energy requirement (Uhlin, 1998), energy use (Vigne et al., 2013), or energy cost (Bleken et al., 2005; Bleken and Bakken, 1997; Refsgaard et al., 1998) in other publications.

In this study, we used data from 20 commercial dairy farms to present the variation in the amount of energy used for production on conventional and organic farms. We analysed the factors that contribute to the entire amount of embodied energy used to produce metabolic energy in milk and meat for human consumption and to highlight solutions for conventional and organic dairy farming separately for reducing energy demand.

2. Material and methods

2.1. Farm selection and description

This study was based on data from 10 certified organic and 10 conventional commercial dairy farms in the county of Møre og Romsdal in central Norway for the years of 2010–2012. The selected farms differed in the 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 latitude 63° N, where the outdoor grazing period is usually not longer than three months for dairy cows. 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). On cultivated areas, only grass and grass-clover leys are grown and irrigation is not needed.

2.1.1. Farm areas

In dairy farming, area-related indicators are important measures for the assessment. The Norwegian Agriculture Agency (NAA) distinguishes between three categories of utilized agricultural area: fully cultivated land, surface cultivated land, and native grassland (Fig. 1). These three categories have different levels of possible management practices and yields. In order to calculate the farm area we multiplied, each hectare of fully cultivated land by 1, of surface cultivated land by 0.6, and of native grassland by 0.3 as suggested by NAA. The weighting of surface cultivated land follows the guidance of Norwegian Agricultural Authority (2011), the factor for native grassland was set to represent an average of the potential grazing yield in these grasslands, based on the experience of the extension service (Rekdal, 2008; Samuelsen, 2004). The sum of these weighted areas is referred to as the 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, is part of the dairy system (DS).

2.1.2. System boundaries

The dairy farm area consisted of fully and surface cultivated land and native grassland used for dairy cows and other cattle. The system boundaries for the dairy system include the dairy farm area and cattle herd, and the 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 the farms had sheep, horses, or sold silage, the area used for grazing, winter fodder, and inputs for non-dairy production was subtracted from the weighted farm area and thus excluded from our calculations in this study.

2.1.3. Farm data and sources

Data from the 20 farms were collected for the calendar years 2010–2012. Inputs and outputs were summed up for the three years and divided by three to calculate average annual values, and thus reducing the influence of weather variations. The information collected included the 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 the quantities and types of products.

The main characteristics of the farms are shown in Table 1. Comparing dairy farm and dairy system area, showed that the dairy farm (DF) area was slightly higher on organic farms compared to conventional farms, while both conventional and organic dairy farms had a dairy system (DS) area of about 60 hectares and a comparable stocking rate per dairy system area. For both type of farms, the off-farm area had an important share, but a bit higher on conventional farms. The conventional farms delivered more milk per cow than the organic farms, resulting in a smaller area needed per litre of milk.

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). Feed demand, grazing uptake, harvest, and weight gain are described in detail by Koesling (2017).

2.2. Farm status

2.2.1. Embodied energy in purchased inputs

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 for the respective continent or European country (Nemecek et al., 2011). The additional energy demand for transportation was calculated using ecoinvent v3.2 (Weidema et al., 2013) in regard to the amount transported, distance from the country of origin to the reseller for the farmers in the project, and different types of transportation used. 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. For the inputs containing nitrogen, we used the declaration of contents when available or the standard nutrient content (NORSØK, 2001). The dry matter (DM) and N contents of concentrates were calculated from the 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 analyses of roughages from three fields on each farm in 2010 and 2011.

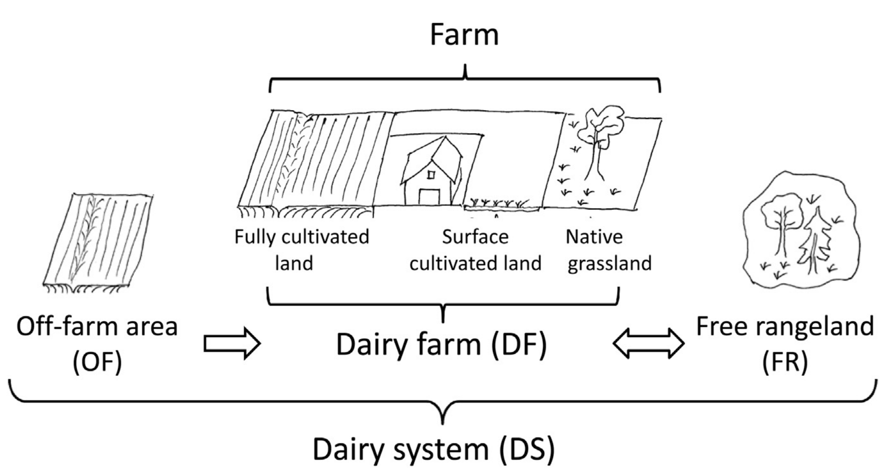

Fig. 1. Different categories of areas for the dairy farm and the dairy system.

Table 1
Main characteristics of the dairy farms.

Parameters	Units[a]	Conventional				Organic			
		min	average	max	standard deviation	min	average	max	standard deviation
Farms	n		10				10		
Dairy farm area (DF); weighted[c]	ha	18	31	85	20	14	36	89	26
Share of peat soil[d] of fully cultivated area	%	0	13	46	18	0	11	43	16
Off-farm area	ha	13	28	65	17	6	25	64	20
Dairy system area (DS)	ha	33	59	150	35	20	61	154	46
Cows per farm	cows $farm^{-1}$	14	30	68	16	15	29	66	17
DF Stocking rate	cows ha^{-1}	0.5	1.0	1.7	0.3	0.6	0.9	1.1	0.2
Live weight cow	kg cow^{-1}	470	570	620	40	400	545	620	75
Milk delivered per cow[b]	kg ECM cow^{-1} $year^{-1}$	6408	7301	8222	582	2751	5490	7317	1679
Diesel use on DF	l ha^{-1} $year^{-1}$	103	179	286	68	35	96	141	36
Working hours on farm	h $farm^{-1}$ $year^{-1}$	2992	4014	4785	507	2522	3802	5026	736
Return to labour per recorded working hour	€ h^{-1}	6.0	14.7	30.9	6.8	9.4	14.5	22.9	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. Energy-corrected milk (ECM) with 3.14 MJ (Sjaunja et al., 1991).
[c] Weighted area = Fully cultivated land +0.6 Surface cultivated land +0.3 Native grassland.
[d] More than 40% organic matter in soil.

While the embodied energy for the inputs are presented in Table 3, free rangeland is an exception. No non-renewable or renewable energy was needed for the production of feed, taken in on free rangeland. The presented values in Table 3 are the calculated amount of the metabolizable energy in milk and meat gain produced on free rangeland.

The energy used to produce imported roughage was calculated as the amount of imported dry matter (DM) roughage multiplied with energy needed to produce one kg DM (MJ kg^{-1} DM). For conventional roughage, we used 1.70 MJ kg^{-1} DM imported roughage as calculated for round bales by Strid and Flysjö (2007) as an estimate because field operations and fertilizing levels in their investigation (50 kg N ha^{-1} by fertiliser and 25 kg N ha^{-1} by farmyard manure) were comparable to common levels in our district. The conditions for producing imported roughages in our district were compared to farm data, local field trials, fertilisation schemes, and information from the local extension service. Also for organic roughages, data from Strid and Flysjö (2007) were used. The energy use for spraying farmyard manure and other field operations was calculated to be 0.66 MJ kg^{-1} DM, slightly higher than on conventional farms, while the amount for harvesting, baling, and film was equal (0.67 MJ kg^{-1} DM). Using no artificial fertilisers and pesticides, the embodied energy for imported organic roughage was estimated to be 1.33 MJ kg^{-1} DM.

The off-farm area needed to produce imported roughage was calculated by dividing the amount of imported roughage with average harvested roughage yields on the farms in our investigation; 4200 kg DM ha^{-1} for conventional and 2940 kg DM ha^{-1} for organic farms.

For different ingredients in the concentrates (all were imported), the values for the area and need of embodied energy for production were taken from ecoinvent V 3.2 (Weidema et al., 2013).

The off-farm area for concentrates was calculated by multiplying the mass of each ingredient with the land occupation (m^2 kg^{-1}).

To calculate the energy needed to raise bought animals, we used the average energy intensity calculated in this study for conventional (2.6 MJ MJ^{-1}) and organic (2.1 MJ MJ^{-1}) farms to produce metabolic energy in 1 kg carcass, and multiplied this value with the expected carcass share (53% of live weight, (Geno, 2014)) of bought animals' weight.

2.2.2. Embodied energy in agricultural buildings and machinery

A 'bottom up' approach based on different building constructions was used to calculate the amount of embodied energy that was required in the production of the building materials in the envelope of the buildings, estimating a 50-year lifetime (Koesling et al., 2015). The building envelope is defined as the materials used to construct and enclose the main building parts, such as the ground- and intermediate-floors, walls (both external and internal), building structure, roof framing, and roofing material. For embodied energy in technical equipment in the barns, values from Kraatz (2009) were used. For embodied energy in building materials (Table 2), we used data from the Norwegian Environmental Product Declarations (Norwegian EPD, 2014) and Fossdal (1995) for the main materials found in the building envelope. In calculating the amount of embodied energy in buildings, the combination of embodied energy per kilogram and the kilogram per square meter in the building parts is important. For aluminium, the share of recycling was estimated to be 80%, for steel 93%. In Norway concrete is rarely recycled up to now.

For each farm, a record of all machinery used in agriculture was prepared, including the 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: tillage machinery, slurry tanker, trailer, tractor, and other agricultural machinery. To calculate the amount of embodied energy per year, the weight of each machine was multiplied by 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 the farm divided by the 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.

2.3. Functional units

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

$$ECM\,[\mathrm{kg}] = milk\,[\mathrm{kg}]\,((en^{fat}\,[\mathrm{J\,g^{-1}}]\,fat\,[\mathrm{g\,kg^{-1}}] + en^{prot}\,[\mathrm{J\,g^{-1}}]\,protein\,[\mathrm{g\,kg^{-1}}] + en^{lac}\,[\mathrm{J\,g^{-1}}])\,en^{mil\ -1}[\mathrm{J\,kg^{-1}}]) \quad (1)$$

In Eq. (1), the standard energy value in Joule for 1 g fat (en^{fat}) is 38.3, for 1 g protein (en^{prot}) 24.2, and the gross energy content in

Table 2
Construction materials with Norwegian values for embodied energy per kilogram and average amount of each material used per cow-place in all buildings on farm for all 20 farms.

Material	Embodied energy (MJ kg^{-1})	Source	Material used per cow-place (kg $cowplace^{-1}$)	Standard deviation
Aluminium plates	106.5	Fossdal, 1995	74	34
Bitumen roof waterproofing, multi-layer	24.4	NEPD 00270E, 2014 [a]	8.2	35.6
Bitumen waterproofing, multi-layer	24.4	NEPD 00270E, 2014 [a]	67	39
Chipboard	12.6	NEPD 00274N, 2014 [a]	47	30
Concrete B 25	0.8	NEPD 123N, 2013 [a]	29,486	7071
Concrete B 35	1.0	NEPD-332-216N, 2015 [a]	16,660	9293
Concrete B 45	1.0	NEPD-334-218-N, 2015 [a]	9539	5193
Concrete reinforcement	8.8	NEPD-348-237E, 2015 [a]	1234	452
Fibreboard, soft, wind barrier	13.9	NEPD 213N, 2011 [a]	108	69
Mortar, dry	1.3	NEPD 00289E, 2014 [a]	30	45
PE-foil waterproofing	65.0	NEPD-341-230-N, 2015 [a]	4.0	1.9
Rockwool	13.4	NEPD 00131E rev1, 2013 [a]	224	117
Steel sheet	46.0	NEPD 00178N rev1, 2013 [a]	14	63
Steel sheet, galvanized	65.3	NEPD 00171N rev1, 2013 [a]	4.0	17.6
Steel, based on ore	19.2	NEPD 00235E, 2014 [a]	9.3	37.6
Timber construction	4.1	NEPD 084N rev1, 2012 [a]	1690	719
Timber, cladding	4.8	NEPD 082N rev1, 2012 [a]	127	47

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

Joule in one kg ECM (en^{mil}) 3,140, while the constant for energy in lactose and citric acid (en^{lac}) is 783.2 (Sjaunja et al., 1991). To show how much energy was used to produce a litre of milk, we present in Fig. 3 the energy use also for Norwegian full-cream milk, which 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). Per 1 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 ECM 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. In this study, we used a system expansion, summing up the content of metabolizable energy in sold milk and meat gain for human consumption in relation to energy produced and per hectare as recommended by Salou et al. (2017).

2.4. Energy inputs, energy outputs and energy intensities

Primary energy embodied in the purchased inputs on dairy farms (SI_{pDF}) was calculated as the sum of the energy needed for production and transportation of different purchased products (I_{pi}) to the farm gate (see Table 3 and Eq. (2)).

$$SI_{pDF} = I_{pa} + I_{pb} + I_{pc} + \ \dots + I_{pn} + I_{po} = \sum_{i=a}^{o} I_{pi} \tag{2}$$

We calculated three main energy intensities. All of them were calculated in MJ input per MJ metabolizable energy in sold milk and meat gain (SO_{mm}) as output (Table 3): energy intensity on yearly purchased inputs ($\varepsilon_{i\text{-}pDF}$); energy intensity on purchased inputs plus the annual value of machinery and buildings (infrastructure) ($\varepsilon_{i\text{-}pDF+Infra}$); and energy intensity on all inputs ($\varepsilon_{i\text{-}all}$), including yearly purchased inputs, the annual value of machinery and buildings and produced metabolizable energy on free rangeland. 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 ($\varepsilon_{i\text{-}pDF+Infra\text{-}FR}$).

These 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 from milk and meat gain for human consumption as denominator (Koesling, 2017).

To investigate if the differences between conventional and organic farms still were significant with higher values of embodied energy of organic concentrates, roughages, and bought animals and lower estimated values for meat gain, *t*-tests were conducted. The values for embodied energy of organic concentrates, roughages, and bought animals were increased to 110% and 120% of the values presented (I_{pa}, I_{pc} and I_{pd} in Table 3). The meat gain on organic farms (O_{meat}) was reduced to 90% and 80%.

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 regression analyses, *t*-tests, variance analyses, and correlation matrices. To reduce the risk of choosing an incorrect model because of correlation between the assumed independent variables (Birnbaum, 1973) when analysing the effect of different variables on intensities, an analysis of variance between the pairs of independent variables were conducted. In the presented models in this study, correlations between the pairs of independent variables were low. Correlations in the matrices were calculated as Pearson's r correlations and the resulting matrices were analysed to detect the relations of variables with different energy intensities. The matrices also allowed us to understand the correlations between the independent variables. The matrices were created for all of the 20 farms. Additionally, separate matrices were created for conventional and organic farms, because different independent variables were significant for the two modes of production.

For descriptive statistics (mean, standard deviation) and figures, Microsoft® Excel® 2013 was used.

To analyse the independent variables that influenced energy intensities and the correlations among them, correlation matrices were calculated. The X_n variables tested ($n = 80$) represent general information about the farms (area and number of animals), the number of working hours, economic results, dairy production, plant production, imports, calculated intensities, and numbers in relation to the dairy farm and dairy system. The variables were

Table 3
The inputs, outputs and formulas used to calculate the energy intensities (ε) used in the present article; energy intensity on purchase ($\varepsilon_{i\text{-}pDF}$), energy intensity on purchase plus infrastructure ($\varepsilon_{i\text{-}pDF+Infra}$), and energy intensity on all input ($\varepsilon_{i\text{-}all}$).

	Index and formula	conventional		organic		t-test[a]
		average	std. dev.	average	std. dev.	
Inputs, primary energy needed to produce		**[MJ ha^{-1} DF]**				
Yearly purchase dairy farm (DF)	I_p					
Concentrates	I_{pa}	18,748	7304	7554	2747	***
Milk powder	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-film	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_{pj}	1679	1338	601	803	*
Pesticides	I_{pk}	32	13	0	26	***
Bedding	I_{pl}	16	16	37	49	n. s.
Transport	I_{pm}	407	149	190	87	***
Fertiliser	I_{pn}	8799	2571	153	2520	***
Lime	I_{po}	88	90	49	66	n. s.
Sum yearly MJ-purchase DF	$SI_{pDF} = \sum_{i=a}^{o} I_{pi}$	48,164	15,001	20,764	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), produced metabolizable energy in milk and meat gain[b]	I_{FR}	770	821	478	747	n. s.
SUM purchase, machinery, buildings	$SI_{pDF+Infra} = SI_{pDF} + I_b + I_c + I_d$	59,203	16,847	29,538	8785	***
SUM all inputs	$SI_{all} = SI_{pDF+Infra} + I_{FR}$	60,743	17,802	30,494	8690	***
Outputs, metabolizable energy		**[MJ ha^{-1} DF]**				
Sold milk, including private use	O_{milk}	20,456	*6457*	12,619	*4146*	**
Meat gain	O_{meat}	3174	*1107*	1911	*478*	**
Sum output (milk and meat gain)	$SO_{mm} = O_{milk} + O_{meat}$	23,631	*7273*	14,529	*4102*	**
Net output without production on free rangeland (FR)	$NO_{mm} = O_{milk} + O_{meat} - I_{FR}$	22,861	*6869*	14,052	*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 infrastructure	$\varepsilon_{i\text{-}pDF+Infra} = SI_{pDF+Infra}/SO_{mm}$	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 infrastructure - FR	$\varepsilon n_{i\text{-}pDF+Infra} = SI_{pDF+Infra}/NO_{mm}$	2.6	*0.4*	2.2	*0.4*	*

[a] The difference between the group of conventional and organic farms was tested by a *t*-test. The differences are 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.

selected based on the results in the literature. The correlation matrices were used to preselect the variables for regression to identify key variables influencing the energy intensities calculated on primary energy for purchase ($\varepsilon_{i\text{-}pDF}$) and all inputs ($\varepsilon_{i\text{-}all}$) as response variables for each farm i ($i = 1, 2, \ldots, n$; $n = 20$ farms). X_{ij} is regressor j ($j = 1, 2, \ldots, p$; $p = 80$) for farm i. e_i are random variables assumed to be independent and normally distributed. $\beta_0, \beta_1, \beta_2, \ldots, \beta_p$, are unknown parameters estimated using the data. The basic forms for the two regression functions were:

$$\varepsilon_{i-pDF} = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \ldots + \beta_p X_{ip} + e_i \quad (3)$$

$$\varepsilon_{i-all} = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \ldots + \beta_p X_{ip} + e_i \quad (4)$$

Because of a low coefficient of determination for conventional farms, a regression was also conducted using a dummy variable, indicating whether the milk yield was higher (1) than the average of the group or not (0). For conventional farms, this variable increased the coefficient of determination (Model 1b and 2b, Table 4), when one farm with a high share of peat soil resulting in low yields was excluded.

3. Results

On average, organic farms produced milk and meat with lower energy intensity on the sum of all inputs ($\varepsilon_{i\text{-}all}$, Table 3) than conventional farms. The summed energy input on the organic dairy farm area was significantly lower compared with the conventional farm area, independent if calculated on purchased inputs, the sum of purchased inputs, machinery and buildings (infrastructure), and all inputs.

Organic farms used 40% of the embodied energy per hectare by concentrates (org: 7554 MJ ha^{-1} DF, con: 18,748 MJ ha^{-1} DF, Table 3) and 56% by fuel (org: 4247 MJ ha^{-1} DF, con: 7575 MJ ha^{-1} DF) of what the conventional farms used. Thus, the sum of the primary energy needed to produce the inputs per hectare on organic farms was 43% of the amount on the conventional farms (org: 20,764 MJ ha^{-1} DF, con: 48,164 MJ ha^{-1} DF). The output (SO_{mm}), measured in metabolizable energy per hectare, on organic farms was 61% of the production on conventional farms (org: 14,529 MJ ha^{-1} DF, con: 22,861 MJ ha^{-1} DF).

Table 4
Results for the different regressions.

Model no, production	Coefficient	Coefficient estimate	Standard error	t-test[a]	R^2 (Model)	Variables
Energy intensities for milk delivered and meat gain as affected by milk yield						
1a, energy intensity on purchase, conventional farms, eq. (3)				*	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} $year^{-1}$)
1b, energy intensity on purchase, 9 conventional farms, eq. (3)				**	0.80	
	α	2.24^{+00}	0.06^{+00}	***		
	β_1	-0.44^{+00}	0.08^{+00}	**		*dummy* X_1 = 1 if milk yield over 8.27 (t ECM cow^{-1} $year^{-1}$)
1, energy intensity on purchase, organic farms, eq. (3)				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} $year^{-1}$)
2a, energy intensity on all input, conventional farms, eq. (4)				*	0.45	
	α	$6.10e^{+00}$	$1.29e^{+00}$	**		
	β_1	$-4.20e^{-01}$	$1.56e^{-01}$	*		X_1 = milk yield (t ECM cow^{-1} $year^{-1}$)
2b, energy intensity on all input, 9 conventional farms, eq. (4)				**	0.67	
	α	2.83^{+00}	0.12^{+00}	***		
	β_1	-0.65^{+00}	0.17^{+00}	**		*dummy* X_1 = 1 if milk yield over 8.27 (t ECM cow^{-1} $year^{-1}$)
2, energy intensity on all input, organic farms, eq. (4)				n.s.	0.28	
	α	$2.70e^{+01}$	$4.49e^{+00}$	*		
	β_1	$-1.10e^{+00}$	$2.16e^{+00}$	n.s.		X_1 = milk yield (t ECM cow^{-1} $year^{-1}$)
Variables influencing the energy input output intensities on purchase on dairy farms ($\varepsilon_{i\text{-}pDF}$)						
3, energy intensity on purchase, all 20 farms, eq. (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. (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 $DF)^{-1}$
	β_3	$-7.96e^{-01}$	$2.68e^{-01}$	**		X_3 = N fixed by clover (all N-input $DF)^{-1}$
5, energy intensity on purchase, organic farms, eq. (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-film used (kg ha^{-1} $year^{-1}$)
Variables influencing the energy input-output intensities on primary energy for all inputs on dairy farms ($\varepsilon_{i\text{-}all}$)						
6, energy intensity on input, all 20 farms, eq. (4)				***	0.53	
	α	$1.65e^{+00}$	$1.76e^{-01}$	***		
	β_1	$1.77e^{-01}$	$3.90e^{-02}$	***		X_1 = N-intensity $N_{i\text{-}pDF}$
7, energy intensity on input, conventional farms, eq. (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 input, organic farms, eq. (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 = Live weight cow (kg cow^{-1})
	β_3	$-6.91e^{-01}$	$1.78e^{-01}$	***		X_3 = N fixed by clover (all N-input on $DF)^{-1}$

[a] The difference between the group of conventional and organic farms was tested by a *t*-test. The differences are significant at level *** < 0.001; ** < 0.01; * < 0.05.

3.1. Contribution of purchase on production 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 in the production of metabolizable energy (SO_{mm}) with 0.38 ± 0.07 MJ ha^{-1} DF and 0.48 ± 0.12 MJ ha^{-1} on organic farms (Fig. 2). The labels in the figure display energy intensities on all embodied energy input. The values are given for conventional and organic farms, with average and linear regression for each group. 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 the lowest production, no organic farm reached the average production level of conventional farms.

3.2. Variations on energy intensities

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 3). In the table, the inputs are given as the amount of primary energy (MJ) needed to produce inputs (I), and content of metabolic energy (MJ) in outputs (O) per dairy farm (DF) hectare per year. The average values and standard deviation for conventional and organic farms are presented. The energy intensities calculated for 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. 2).

Energy intensity of organic farms was lower than that of conventional ones, but the share of infrastructure in total energy use was higher for the organic farms (Fig. 3). In the figure, values for conventional (con) and organic (org) dairy farms and the contribution of energy from different inputs are presented. 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 ($\varepsilon_{i\text{-}all}$). The 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 L milk. Below the figure, milk yield per cow in kg

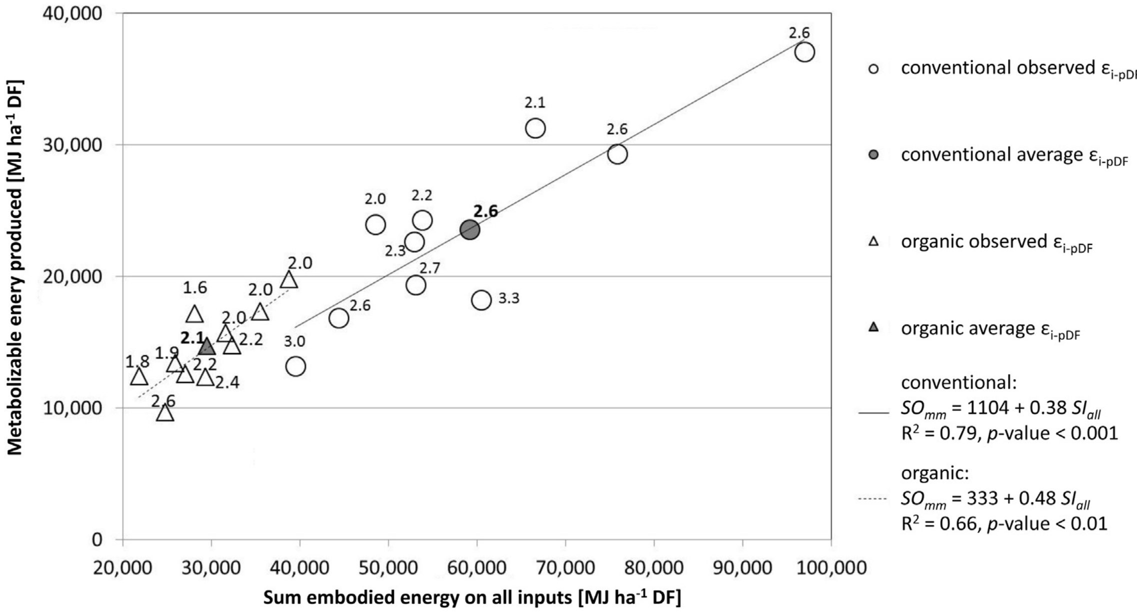

Fig. 2. Production of metabolizable energy in milk and meat gain per dairy farm (DF) area (vertical axis) in relation to embodied energy input on all input per dairy farm area (horizontal axis).

ECM cow^{-1} year^{-1} and energy intensities without free rangeland are presented. The data are listed in Table S1 (supplementary materials).

For the farm with the lowest average milking yield (2980 kg ECM cow^{-1} year^{-1}), including the 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, the influence of infrastructure varied from 15% to 43%. The average value on conventional farms was 19% and on the organic farms was 29%.

3.3. Milk yield and energy input output intensities

In conventional farms, increasing milk yields per dairy cow showed a tendency to result in lower energy intensities on purchased inputs ($\varepsilon_{i\text{-}pDF}$, Table 4 and Fig. 4 (a)) and on all energy inputs ($\varepsilon_{i\text{-}all}$, Fig. 4 (b)). Conventional farms that had cows with a higher milk yield than average, had lower energy intensities on purchased inputs and on all inputs than average (Model 1b and 2b). One conventional farm produced food with a slightly lower intensity ($\varepsilon_{i\text{-}all} = 2.1$) than the average of organic farms, and two other farms produced with intensity close to the average of organic farms (Fig. 4 (b)).

On organic farms, the energy intensities were not influenced by the variation in milk yield (3.0–8.3 t ECM). The influence of infrastructure on total energy intensity was larger on organic farms, especially on those with low milk yields.

3.4. Correlation between variables tested

The dependence of multiple variables on intensities, were investigated by correlation matrices (data not presented). On conventional farms, there was a high correlation between nitrogen (N) intensities (Koesling, 2017) and energy intensities on purchase ($\varepsilon_{i\text{-}pDF}$). The dairy farm area was positively correlated with energy intensities on purchased inputs and infrastructure ($\varepsilon_{i\text{-}pDF+Infra}$) and all inputs ($\varepsilon_{i\text{-}all}$). On organic farms, the dairy farm area was also positively correlated with energy intensities on 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 more working hours per hectare (h ha^{-1} year^{-1}) and per metabolizable energy produced (h MJ^{-1} year^{-1}).

The energy intensity on purchase on the 20 dairy farms (Model 3, Table 4) was highly correlated ($R^2 = 0.88$) with the nitrogen intensity on purchase ($N_{i\text{-}pDF}$). Since conventional and organic farms produce with different N intensities (Koesling, 2017), the explanation of this model mainly reflects the different nitrogen intensities between conventional and organic farms. The conventional farms had a higher energy intensity on purchase ($\varepsilon_{i\text{-}pDF}$) when more diesel per hectare was used; they had a higher share of N fertiliser per hectare and a lower share of N fixed by clover per hectare of all N-input per hectare of dairy farm (Model 4, Table 4). On organic farms, the energy intensity on purchase ($\varepsilon_{i\text{-}pDF}$) increased with lower harvestable yields per hectare and an increased use of PE-film for silage (Model 5, Table 4). Models 4 and 5 had high values for coefficient of determination, (0.91) for conventional (Model 4) and (0.86) for organic farms (Model 5).

The model explaining the energy intensity $\varepsilon_{i\text{-}all}$ on all inputs with the nitrogen intensity $N_{i\text{-}pDF}$ as the variable on all 20 farms had

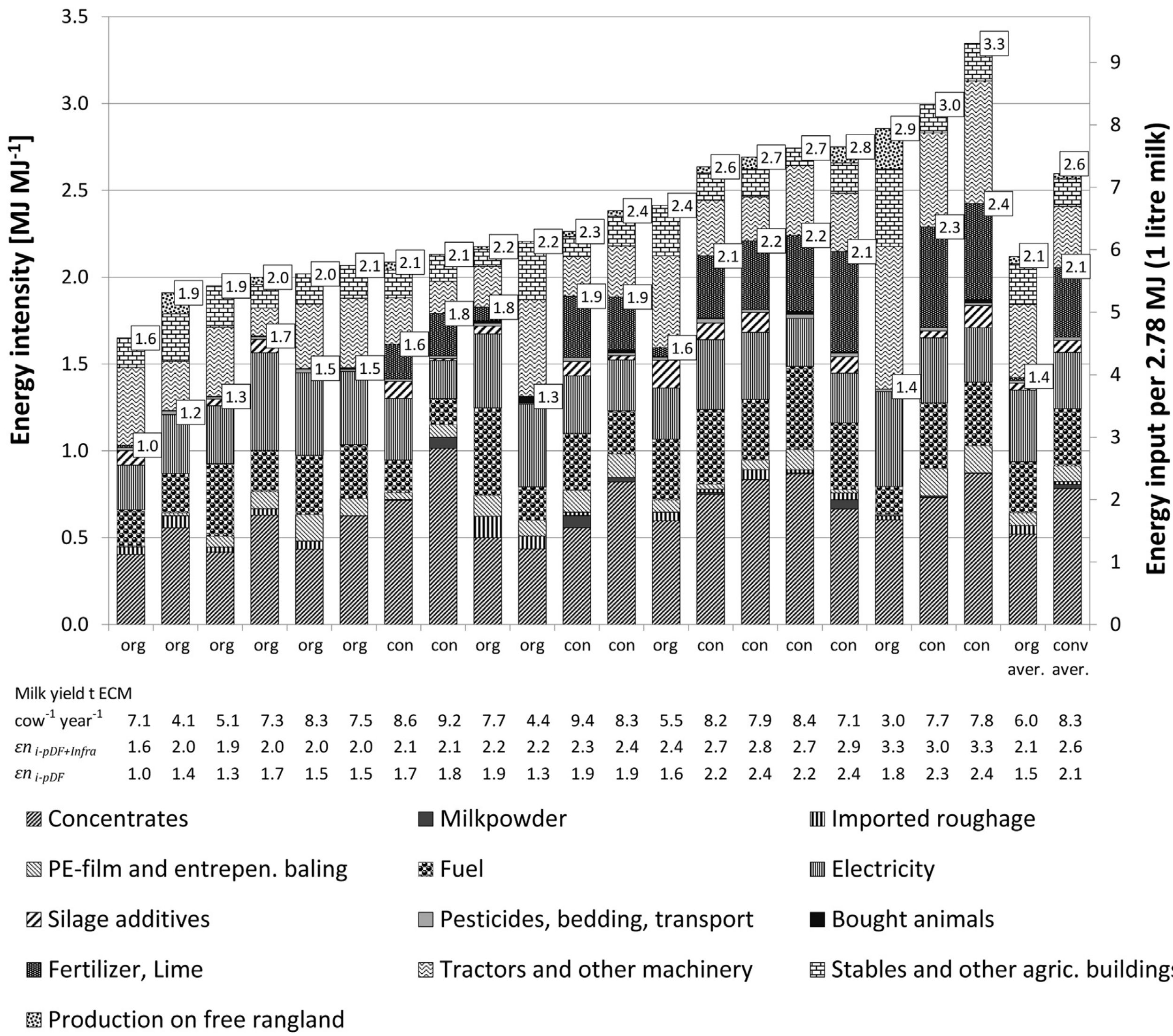

Fig. 3. Energy intensity is the amount of primary energy needed to produce 1 MJ metabolizable energy in delivered milk and meat gain (left axis).

a lower coefficient of determination ($R^2 = 0.53$, Model 6, Table 4).

On conventional farms, the energy intensity $\varepsilon_{i\text{-}all}$ on all inputs could be described satisfactorily ($R^2 = 0.96$) by Model 7 with only two variables. The energy intensity $\varepsilon_{i\text{-}all}$ was positively correlated with the sum of tractor weight per hectare and N intensity calculated on purchased products ($N_{\text{i-pDF}}$). 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 live weight of the cows, and less nitrogen fixated by clover as a part of all nitrogen used on the dairy farm.

4. Discussion

The main findings of this study are that organic dairy farms produce milk and meat on average with less energy than conventional dairy farms, independent if measured per area or amount produced. The variations within each mode of production were high and in this section the results are discussed in regard to literature, uncertainty and the influence of factors.

4.1. Energy intensity

Our obtained energy intensities of 7.2 MJ kg^{-1} ECM on conventional and 5.8 MJ kg^{-1} ECM on organic dairy farms, are much higher than corresponding results from Denmark of 3.6 MJ kg^{-1} ECM and 2.7 MJ kg^{-1} ECM, respectively (Refsgaard et al., 1998). This is the only study we found in the literature on energy intensity on purchase and infrastructure in conventional and organic milk production. The lower values in Denmark can be caused by the higher yields and larger fields and shorter distances to them in that country compared to Norway. Another reason for lower values found in Denmark is expected to be due to the method, where standard values were used for the quantity of machinery and buildings in contrast to our study, and the fact that the Norwegian dairy farming can be characterized by an intensive use of machinery and fossil fuel (Vigne et al., 2013).

Modelling the farms for future dairy farming in Germany, Kraatz (2012, 2009) calculated 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 less embodied energy in stables (modelled for 180 cows). Refsgaard et al. (1998) suggested that using standard values for field operations could underestimate the use of diesel by nearly 50% compared to data from real farms. Thus, the use of standard values may cause an underestimation of the real energy use on farms.

Including both the purchase and machinery on French dairy farms, Werf et al. (2009) calculated lower energy intensities and a smaller difference between conventional and organic production (2.8 and 2.6 MJ kg^{-1} ECM) than in our study (6.7 and 5.2 MJ kg^{-1} ECM). Due to the correlation of N-fertiliser and energy intensity and the high N-surplus on conventional farms (Koesling, 2017), a reduction of N-fertiliser and the N-surplus should be possible on most conventional farms without reducing yields, if the utilisation of farmyard manure is improved (Cortez-Arriola et al., 2014). Using less N-fertiliser will reduce energy intensities as also observed by Werf et al. (2009), where conventional dairy farmers only used 60 kg N ha^{-1} on average. However, similar to our study, Werf et al. (2009) also found a high variation within both groups.

In this study, different energy intensities were calculated on purchased inputs, machinery, and buildings, so the results can be compared with other European studies. Similar to this study, all the other studies analysing both conventional and organic dairy farms calculated lower energy intensities for organic milk production (e.g. Cederberg and Flysjö, 2004; Thomassen et al., 2008; Werf et al., 2009).

4.2. Uncertainty

The implication of different sources of uncertainty for the reliability of Life Cycle Assessment (LCA) in general and in agriculture has received more attention in the last years (Basset-Mens et al., 2009; Ross et al., 2002; Röös et al., 2010). In LCA, there are two main sources of uncertainty, poor data quality and lack of site-specific data (Ross et al., 2002). For plant production, the actual yield was found to be the most influential parameter. Also N fertilizing and soil processes have a high impact on the carbon footprint (Röös et al., 2010).

In contrast to a LCA, neither yields or soil processes are needed for this study on the use of energy. For purchased inputs and delivered milk, we used accounting data, which can be assumed to be of high data quality. For machinery and buildings, registrations were done on farm, to get farm specific data. For buildings, the building construction approach was used to get reliable data on materials used and the amount of embodied energy (Koesling et al., 2015).

For the amount of embodied energy, we tried to get site specific data either directly from ecoinvent or MEXALCA. For building materials, we used data for Norway, and for concentrates we used data for the different ingredients, specific for each farm and year.

Of the inputs included, embodied energy from stables and other buildings, machinery, fertiliser, lime, pesticides, bedding, transport, silage additives, electricity, fuel, PE-film, entrepreneurial baling and milk-powder have the same origin, independent if they are used on a conventional or organic farm.

Uncertainty about different embodied energy for conventional and organic inputs can be restricted to the inputs from the bought animals, imported roughages and concentrates, and the meat gain as output.

Organic dairy farming was found to produce milk and meat on average with less energy than conventional dairy farms, independent if measured per area or amount produced. To evaluate the influence of data uncertainty, we recalculated the results presented in Table 3 for input and output data on organic farms which may have higher uncertainty (see 2.4 Energy inputs, energy outputs and energy intensities).

With an increase of the values for concentrates, imported roughages or bought animals, or a reduction of the meat gain on organic farms there were still significantly lower energy intensities on organic farms than on conventional.

Data quality and harmonisation is an important topic for ecoinvent (Frischknecht and Rebitzer, 2005), thus, it is unlikely that the values for embodied energy for organic inputs are underestimated, while the values for conventional are expected to be correct.

4.3. 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. A linear correlation between increased milk yield and lower energy intensity was expected, based on previous studies on conventional dairy farming (Garnsworthy, 2004; Gerber et al., 2011; Kraatz, 2012; Yan et al., 2013). However, we could not find a linear correlation between increased milk yield and lower energy intensity on conventional farms. But having cows with a milk yield above average was found to be correlated with lower energy intensity. The three farms with the highest milk yield had the lowest energy intensities (Table 4 and Fig. 4). Consistent with the results by Smith et al. (2015), organic dairy production was associated with better energy utilisation than conventional production both on area basis (energy intensity per area and on product basis). We could not identify any other studies stating that energy intensities on organic farms are unaffected by milk yield, which is an important finding of this study and a benefit from including organic dairy farms with high variation in milk yield. Many factors can contribute to produce with low energy intensities despite low milk yields. These factors are nitrogen fixation by clover, buildings with less embodied energy, storing of silage in towers, small machines, farm area close to the farm, smaller farms, and more grazing. Many of these factors contribute to use less inputs which are linked to embodied energy.

4.4. Farm size

Conventional farms with larger areas had higher energy intensities both on purchase ($\varepsilon_{i\text{-}pDF}$) and all inputs ($\varepsilon_{i\text{-}all}$) and had higher tractor weight (kg ha^{-1} $year^{-1}$). This is in line to the results of Hersener et al. (2011) for comparable farms in Switzerland who observed higher energy intensities on larger farms, and an increasing environmental costs of intensification (Antonini and Argilés-Bosch, 2017). For organic farms, the overall energy intensity did not increase with larger farm area, but these farms used more diesel (l ha^{-1}). The narrow valleys in the region combined with small fields and rented areas may caused that an increase in the farm area, increased the distance to the fields significantly, requiring more diesel fuel for transport. The climate, with a few days for harvesting under optimal conditions, might explain why farmers buy bigger tractors; to be able to harvest a larger area within the available “harvest window”.

4.5. Increased grazing can contribute to reduced energy intensity

Grazing can contribute to reducing energy intensity as reported by O'Brien et al. (2012), Kraatz (2012), and Vigne et al. (2013). Not surprisingly, for all farms, higher energy uptake by grazing relative to the entire energy uptake by cattle reduced the use of PE-film for silage (kg PE-film ha^{-1} $year^{-1}$). Grazed feed does not have to be harvested or packed as round bales. Grazing free rangeland had on average little effect on the energy intensities of conventional and organic farms. One reason is that not all had access to free rangeland. However, for some farms grazing had a large impact. For the organic farm with the highest overall energy intensity $\varepsilon_{i\text{-}all} = 2.9$

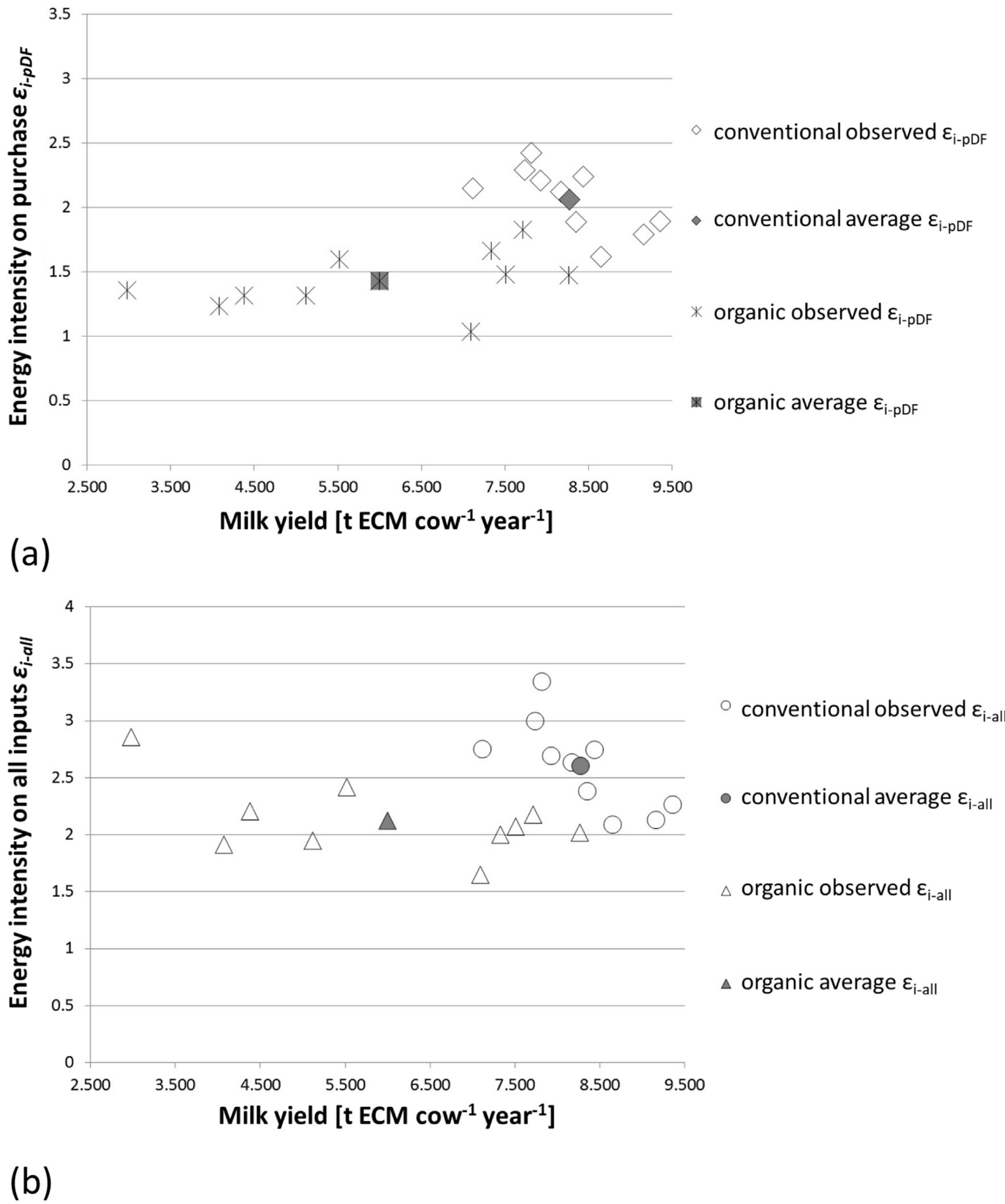

Fig. 4. (b) Energy intensities on purchase (a) and on all inputs (b) in relation to milk yield. Values for conventional and organic farms, with average and linear regression on milk yield for each group.

(Fig. 3), the intensity calculated without grazing free rangeland was even higher ($\varepsilon n_{i\text{-}pDF+Infra} = 3.3$). Increased grazing on native grassland and free rangeland can lead to higher milk and meat production without occupying additional land, where crops can be grown for human consumption.

4.6. 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. For farms with low milk yield it is thus important to reduce the amount of embodied energy in buildings and machinery, but this is difficult in the short run. Good maintenance for a longer lifetime expectancy of buildings and machinery would gradually reduce the share of embodied energy from infrastructure in dairy products. When making investments, the focus on material savings by choosing building characteristics properly (e.g. a design with less square metre of ground floor area and less square metre of insulated walls) and the increased use of materials with lower primary energy demand during production (e.g. wood instead of concrete) would reduce the relative amount of primary energy, which is discussed by Dux et al. (2009) and

Koesling et al. (2015). However, it is still difficult for farmers to get the necessary 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 by Harris and Narayanaswamy (2009). These include: their small influence on overall results (Flysjö et al., 2011); the inclusion of embodied energy is time consuming; there is a lack of data; or 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) calculated the values for energy intensity for producing milk ranging from 3.7 MJ kg^{-1} ECM to 12.3 MJ kg^{-1} 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 of embodied energy and how to reduce it is crucial, because infrastructure can have an important contribution to the overall energy use as shown in the present study and found by Marton et al. (2016).

Comparing the energy intensity of conventional and organic dairy farming based only on purchase would prove the superiority of organic dairy production to conventional production (only 67% of the energy intensity of conventional farms; $\varepsilon_{i\text{-}pDF}$ 1.4 for organic compared to 2.1 for conventional). However, when embodied energy for infrastructure is included, the energy intensity of organic farms was 81% of the value for conventional farms ($\varepsilon_{i\text{-}all}$ 2.1 to 2.6, respectively, Fig. 3). Focusing on the energy intensity on all inputs will result in better recommendations to reduce the overall energy use in dairy production than focusing only on the energy intensity on purchases.

5. Conclusion

The objectives of this study were to analyse the differences in energy intensities of conventional and organic dairy farms, the influence of machinery and buildings on the intensities, and the solutions to reduce the energy intensities of conventional and organic farms.

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. More important than this, is the high variation found for both modes of production, indicating that it should be possible to reduce the use of energy on many farms, regardless of the production mode.

Because the share of embodied energy from machinery and buildings on dairy farms varied from 15% to 44% of the entire consumption of embodied energy, we recommend that analyses and strategies to reduce energy intensities in dairy farming should include embodied energy on machinery and buildings. Future work should focus on how to reduce the amount of embodied energy in machinery and buildings.

For conventional and organic dairy farms, we recommend different strategies to reduce the energy intensity on all inputs. Conventional farms can reduce energy intensity by reducing the tractor weight (measured as the weight of all tractors on farm per dairy farm area). Due to high nitrogen surplus on most conventional farms, it should be possible to reduce the use of nitrogen fertilisers without reducing yields. On organic dairy farms, energy intensity can be reduced by reducing embodied energy in barns, and by increasing the yields. Increased amount of clover in leys and thus higher nitrogen fixation by clover are among others important to increase yields on organic farms. The embodied energy in existing barns can be reduced by a higher milk production per cow and by a longer use of the barns than the estimated lifetime of 50 years. In the long run, new barns should be built with a lower amount of embodied energy. Reduced embodied energy in barns can be achieved by less square metre area per cow-place in the barn, less square metre area of concrete walls, and less square metre area of insulated concrete walls.

The high variation of energy intensity on all inputs from 1.6 to 3.3 (MJ MJ^{-1}) (4.5–9.3 MJ kg^{-1} milk) found on the 20 farms shows the potential for producing with low energy input and indicates that individual farm analyses are preferable as a basis for developing individual solutions to reduce energy intensity. Future work is needed to analyse in detail the reasons for high energy intensities and possible improvements. Inefficiencies can be found many places as e.g. plant production, harvesting, storing, feeding, utilisation of feed, animal health, handling of manure, buildings and technical equipment. It can be expected that the utilisation of energy can be further improved even on the best farms, since none of the farmers received information about how to reduce the amount of embodied energy.

Nevertheless, focusing on the important variables for the energy intensity identified in this study is a good starting point for finding solutions to reduce energy intensity of conventional and organic dairy farms with similar conditions.

The presented approach of using energy intensities highlights the influence of embodied energy from different inputs, and can be used to analyse farms and find possible solutions to improve the farms' overall energy utilisation.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2017.06.124.

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