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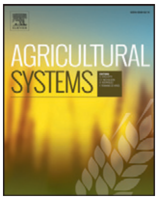

An assessment of the energy footprint of dairy farms in Missouri and Emilia-Romagna

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ABSTRACT

The strong dependence of the livestock sector on fossil fuel could be challenged in a matter of decades or sooner, either by rising fossil fuels prices of by the commitments foreseen under carbon emission reduction protocols. In this context, it is relevant to assess the energy footprint of animal products and to identify potential strategies for the transition towards a greater reliance on renewable energy.

The present research was based on a comparative analysis of milk production systems in Missouri, USA and in Emilia-Romagna (EU NUT 2), Italy. A total of fifteen dairy farms, either grain based, forage based or organic, were investigated, using data on direct (fuel and electricity) and indirect (structures, machinery, feed, fertilizers, pesticides, seeds) energy inputs. All inputs were reported in the functional unit of 1 kg of Energy Corrected Milk (ECM). The impacts of feeding practices, fertilizer use intensity and organic methods on energy consumption levels were evaluated and discussed.

Emilian farms showed a lower energy input than Missouri farms, mainly due to their greater reliance on alfalfa as feed, and less use of fertilizers and fuel. Forage based farming was more energy efficient in Missouri, while organic farming was more efficient in Italy.

This research suggests that policy interventions could lead to lower energy input dairy systems by promoting reduced use of fertilizers, and by minimizing waste along the milk supply chain, and thereby encouraging a more sustainable industry.

1. Introduction

Since the diffusion of the lactase persistence genetic mutation in Europe (Leonardi et al. 2012), cow milk and related products have become an important element of the daily diet, both in the old world and in the so called “new Europes” (Cosby, 2004). World production in 2013 was 770 Mt, or 90 kg per capita per year, supplying about 10% of protein and 6% of energy daily intake. Consumption levels are higher in North America (253 kg) and in Europe (240 kg), where milk and its derivatives constitute 20% of protein and 10% of energy intake (FAOSTAT, 2015).

Due to the importance of dairy products in the human diets of a large part of the world, the dependence of this sector on non-renewable fossil energy and the influence of various farming practices on the energy footprint of the dairy sector are crucial issues for the transition of food systems towards less carbon intensive practices.

Several studies assessed the energy inputs of dairy farming in New Zealand (Wells, 2001, Hartman and Sims, 2006) and Northern Europe: Finland (Grönroos et al. 2006, Mikkola and Akolas, 2009), Estonia (Frorip et al. 2012), Denmark (Refsgaard et al. 1998), Sweden (Cederberg and Mattson, 2000), Norway (Eide, 2002), Germany (Haas et al., 2001, Kraatz, 2012), Ireland (O'Brien et al. 2012, Upton et al. 2013), Belgium (Meul et al. 2007) and the Netherlands (Thomassen et al. 2008). European studies have mainly focused on grain based systems, both conventional and organic, with substantially no consideration to forage based farming. Little attention has been paid to Southern Europe (Castanheira et al. 2010), while for North America, Pimentel and Pimentel (2008) has addressed the milk sector only marginally.

This research is aimed at analyzing, from a comparative perspective, the energy inputs necessary for the production of cow milk in one region of Southern Europe (Emilia-Romagna, Italy) and in one state of North America (Missouri, USA). These two geographical contexts share key common features, such as population size (respectively 4.4 and 6 million inhabitants) and GDP per capita, around $42,000 to$45,000 per year in the 2011–2013 period (Eurostat, 2013). The average herd sizes are comparable, while the Italian region is characterized by higher number of farms and cows and by greater milk productivity (+30%), (see Table 1).

Production is almost stable in the Italian region, while the dairy sector in Missouri has continuously declined over the last 40 years from over 300,000 milking cows in 1975 to less than 100,000 in 2013 (MU,

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Table 1
Indicators for milk production in Missouri and Emilia-Romagna.

Indicator	Missouri	Emilia-Romagna
Number of farms	1248[a]	4266[c]
Number of cows	92952[b]	303023[d]
Average herd number	74	71
Milk production (kt)	605[a]	2576[d]
Milk per cow (kg)	6514	8502

Source:
[a] Horner et al. 2015.
[b] USDA, 2012a, b, c and d.
[c] Benini and Pezzi, 2011.
[d] CLAL, 2013.

Table 2
Farms surveyed in the case study according to the use of chemicals and type of feed.

Farm		Herd size (N)	Farm area (ha)	Lactations (N)	Milk per cow (kg yr^{-1})	
					Raw	ECM
Missouri	G1	187	–	2.25	11408	12083
	G2	30	8,2	3.5	6622	9303
	F1	95	83	2.25	5835	6691
	F2	547	160	4.0	3976	4599
	O1	49	49	6.0	4139	4580
	O2	45	45	6.0	6804	7783
	O3	67	67	3.0	3049	3622
Emilia Romagna	G3	850	820	2.25	10706	11334
	G4	587	400	3.1	9478	10473
	G5	1250	1225	2.3	10694	10950
	F3	36	25	3.0	7188	7682.7
	F4	45	19	2.37	6154	6944
	O4	42	26	4.0	6129	6456
	O5	48	36	4.5	7368	7588
	O6	180	140	3.5	9125	9359

Source: authors' elaboration. Farm G1 has no owned land since it purchases all feed.

2000, USDA, 2014) mainly due to the competition from other States, like California and Wisconsin, where farming is more intensive and milk production has increased by a factor of 4 and 1.5 respectively in the same period (USDA, 2012c). However, pasture based dairying is becoming more popular in Missouri and could reverse this declining trend in the near future (Ikerd, 2009). Final consumption presents a different picture: milk from farms in Emilia-Romagna is utilized mainly for the production of Parmigiano Reggiano, whose tradition dates back at least to the Middle Ages (Boccaccio, 1351), while in Missouri most milk is directly consumed and only a fraction is used to produce cheese. For this reason, the present study is limited to energy use up to the farm gate, in order to compare similar products.

2. Materials and methods

This study was based on data from fifteen dairy farms, seven located in Missouri and eight in Emilia. This small sample size was necessary because of the very intensive nature of data collection process. This approach is comparable to most studies of this nature. The greater detail required for this type of analysis makes a smaller sample necessary. The farms were chosen using a snowball sampling approach; discussions with experts and suggestions from the same farmers allowed us to identify a suitable sample of farms.

Three farming systems were studied:

(i) *grain based* (*G*), when cereals, soy and other by-products constitute more than 40% of the mass of the total daily ration;
(ii) *forage based* (*F*), when pastures or hay represent more than 60% of the diet;
(iii) *organic* (*O*), when all feed and fertilizers follow the regulatory requirement for organic certification. In principle, organic may be grain or forage based, but all organic holdings surveyed for this study were predominantly pasture and hay based.

Forage based farms use different feeding practices in the two regions. In Missouri, animals are kept on pasture all year, directly pasturing, while in Emilia-Romagna cattle are confined to barns, and alfalfa and grass are mechanically cut and dried to provide the feed.

All farms are indicated by a code to ensure the confidentiality of respondents: grain based farms (G1, G2, G3, G4 and G5), forage based farms (F1, F2, F3 and F4) and organic forage based farms (O1, O2, O3, O4 and O5). Farm characteristics are shown in Table 2, while their approximate locations are indicated in Fig. 1.

2.1. System boundaries and functional units

Given the goal of this study, a cradle to farm gate perspective was adopted. As shown schematically in Fig. 2, the system boundary included all direct energy inputs occurring at the farm level (fuels and electricity) and all indirect energy inputs immediately related to:

- building construction (barns, feed storage facilities, warehouses and parlors);
- machinery manufacturing (tractors and implements);
- forage and grain grown on the farm for milking cows and heifers;
- forage and crops purchased on the market.

The methods employed to compute indirect inputs are detailed in the following paragraphs. All information on direct energy inputs, structures, machinery, materials and feed were collected during field visits

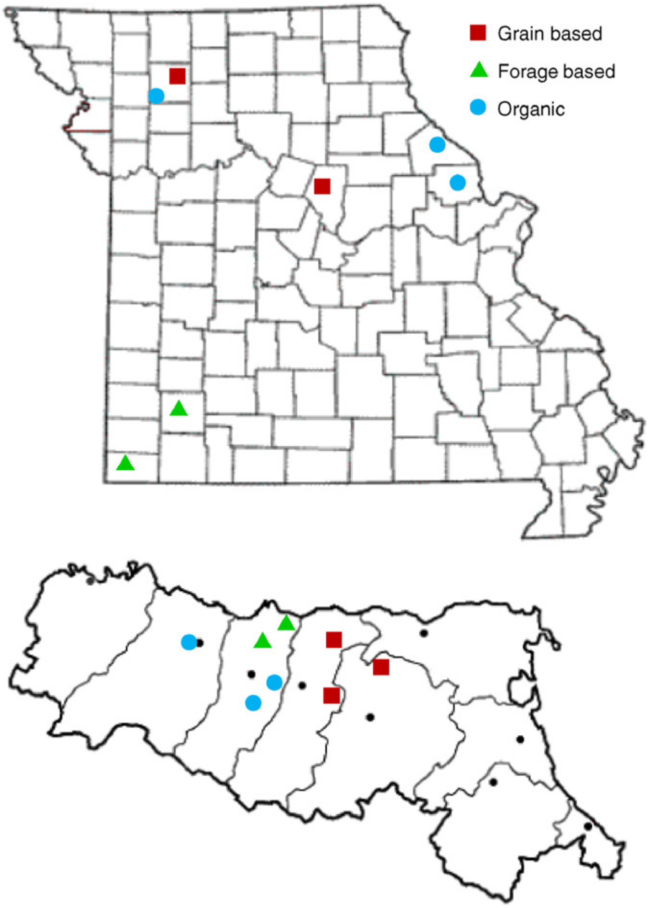

Fig. 1. Location of surveyed farms within the State of Missouri (above) and the Emilia-Romagna region (below). The two maps are not drawn on the same scale.

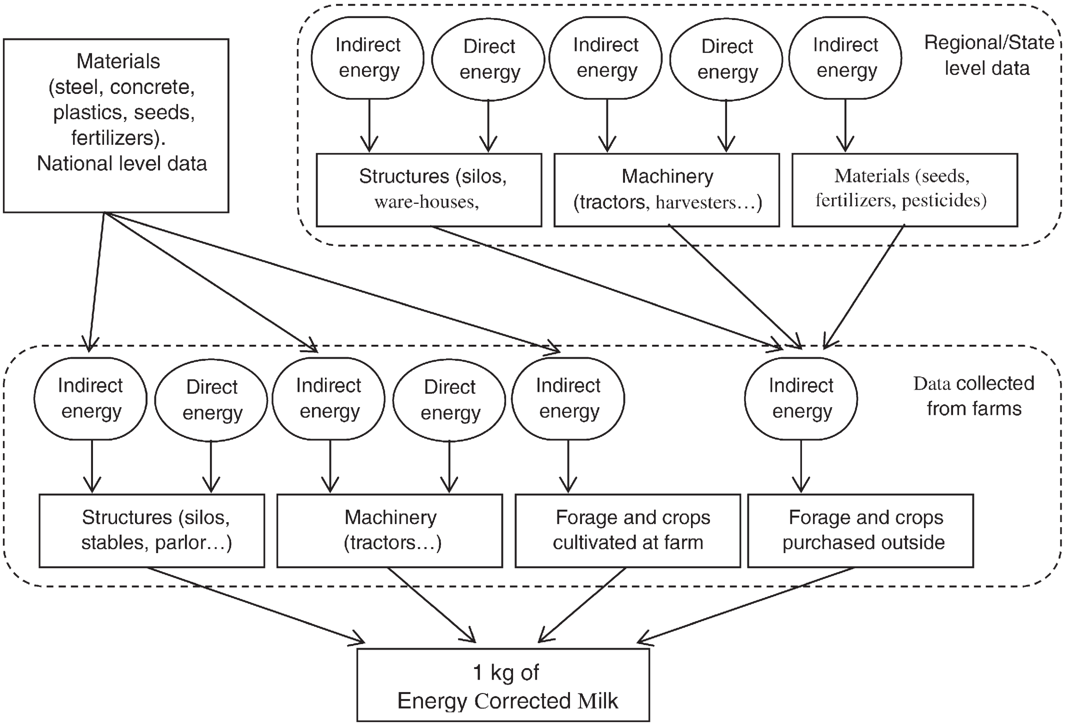

Fig. 2. Scheme for the assessment of direct and indirect energy inputs for milk production.

and interviews with farmers. The complete list of all indicators obtained from the interviews is reported in Table 3.

Some feeds used by the dairy farms, mainly silage and grains, were purchased from the market. This required a detailed analysis of the energy needed to produce silage and grains, taking into account structures, machinery and materials (see Fig. 2). Since the feed was bought on the market, regional or state level data were used to calculate energy inputs.

The analysis did not include two factors: (*i*) energy consumption for transport of equipment and materials to the farm, since it was not possible to track the whole logistic of production inputs; (*ii*) background inputs, such as the energy used to build the factories producing fertilizers or machinery, or the banks and the law offices involved in granting loans and arranging contracts.

These two factors account for up to about 10% of the total energy costs, so the boundaries defined for the present study included about 90% of all inputs. According to the *Economic Input Output Life Cycle Assessment* system (Hendrickson et al., 2006), in the US transport energy represents 5.1% of the total energy for milk production, while all other costs that aren't included in this analysis comprise 5.5% (the analysis was run on the www.eiolca.net site and is related to the US 2002 Benchmark related to producer prices). Thus it is estimated that these two factors account for approximately 10% of the total energy costs, and that our analysis includes about 90% of all energy inputs.

Given our energy system boundary and our focus on the production of milk up to the farm gate without further processing — the functional unit of 1 kg of raw *Energy corrected milk* (ECM) at the farm gate was used. This unit allows the comparison of milk products with different protein and fat contents, by converting them into equivalent units with 3.5% fat and 3.2% crude protein content (3.2% crude protein content is equivalent to 3.01% of true protein content plus non-protein nitrogen). In order to perform this normalization, actual milk production was multiplied by the following dimensionless factor (Tyrrel and Reid, 1965, DRMS 2014):

$$ECM = 12.97\,f + 7.65\,p + 0.327, \tag{1}$$

where f is the fat fraction and p the true protein fraction. The annual production of one (average) milking cow was used to evaluate the performances of farms with different cow productivities.

2.2. Energy for structures, machinery and equipment

The energy embodied in steel is 35.3 MJ kg^{-1} for new material and 9.5 MJ kg^{-1} for recycled material (Hammond & Jones, 2008). Thus, the average energy content is estimated to be 18.5 MJ kg^{-1} of steel, since about 65% of steel was recycled in the US in the period 2008–2012 (Papp, 2012). The specific embodied energy in steel silos was therefore calculated to be 0.05 ± 0.01 GJ m^{-3} yr^{-1} for volumes greater than 50 m^3, using mass data from silo manufacturers and assuming a lifespan of 30 years (DLGF, 2011). The embodied energy per unit of feed mass is then 0.07 ± 0.01 MJ kg^{-1} for maize and 0.20 ± 0.04 MJ kg^{-1} of dry matter of maize silage and alfalfa and hay silage. The higher value for alfalfa and hay is due to their lower density, which means that 1 kg of silage occupies more volume than 1 kg of grain.

Soybeans or soymeal are usually stored in flat warehouses, thus a 100 × 50 m flat grain warehouse with a single 16 m high pitched roof, with precast concrete walls, a steel lattice and a PVC fabric was assumed. Steel and concrete mass values were computed according to a density for unit of floor area of 50 kg m^{-2} for steel and 2660 kg m^{-2} for concrete (Steel construction, 2011; Hanson, 2015). It was assumed that the effective soybean storage volume is one half of the geometrical volume of the building. Concrete has the highest embodied energy input, 25,200 GJ (Hammond & Jones, 2008), corresponding to a yearly value per kg of stored soybean of 0.04 MJ kg^{-1} yr^{-1}. Steel structure contributes another 0.007 MJ kg^{-1} yr^{-1}, while embodied energy in PVC is almost negligible.

The energy embodied in machinery was estimated at 80 MJ kg^{-1} of equipment (Stout, 1991); more recent analysis of tractors and related equipment (Mikkola and Ahokas, 2009) confirms this value, since the reduction in the use of steel and iron has been offset by the increased use of the more energy intensive aluminum and synthetic materials. The total input energy rises to about 140 MJ kg^{-1} once repair, service

Table 3
Information collected at the surveyed dairy farms.

Farm and animal data	Nominal variable	Typology (grain based, forage based, organic)
	Number	Milking cows
	Number	Calves born during last year
	Years	Average age of herd
	Number	Average number of lactations
Data on forage production, detailed for corn silage, corn, barley, pasture, alfalfa, other hay, other forage	Hectares (ha)	Cultivated area
	kg ha^{-1}	Yield
	kg ha^{-1}	Nitrogen/Phosphate/Potash use intensity
	kg ha^{-1}	Herbicides/Insecticides/Fungicide use intensity
	%	Quote of feed covered by self-production
Feeding inputs, detailed for cows in high milk production medium production or dry period.	kg day^{-1}	Corn silage/corn
	kg day^{-1}	Barley
	kg day^{-1}	Pasture (estimated)
	kg day^{-1}	Alfalfa/Other hay
	Kg day^{-1}	Soy bean meal
	kg day^{-1}	Dried distillers grains and solubles
	kg day^{-1}	Premix (with composition)
Structures and machinery, detailed for each tractor or other equipment	Number	Stalls in milking parlor
	h day^{-1}	Working time
	kg day^{-1}	Materials used
	kW	Power of tractor
Direct energetic inputs	l year^{-1}	Diesel/gasoline fuel use
	l year^{-1}	Propane use
	KWh year^{-1}	Electrical energy
Outputs	kg	Total raw milk production
	%	Butterfat fraction
	%	Protein fraction

and maintenance are included (Giampietro, 2002, Mikkola and Ahokas, 2009). The masses of machinery were estimated from their power, using an average mass/power ratio of 60 kg kW^{-1} (Lazzari, 2015). In the USA, the lifespan for all machinery was assumed to be 40 years since in the last ten years the average yearly rate of machinery turnover was around 2.5% (USDA, 2012a, b, c and d). In Italy, the lifetime for tractors and combines was estimated to be 52 years by considering the machinery stock and the renewal rate (Federunacoma, 2002).

The embodied energy in milk parlors increases linearly with the number x of cow stalls according to the relation $E = 24.2x + 293$ GJ (Wells, 2001). Assuming a lifetime of 30 years (DLGF, 2011), the average annual energy input is $e = 0.81x + 9.77$ GJ year^{-1}. Depending on the efficiency of operations, one stall can generally accommodate from 12 to 32 cows milked twice a day (Smith et al., 2003), so the input per cow should be reduced by the same factor. Taking into account that the average Missouri productivity is around 6500 kg of milk per cow (Table 1), the specific embodied energy of milking parlors per kg of milk and year is almost negligible, ranging from 0.005 to 0.025 MJ kg^{-1}.

The embodied energy in dairy stables is slightly higher: 1.5 ± 0.8 GJ per cow per year (Koesling et al., 2013), which is equivalent to 0.1–0.3 MJ kg^{-1} of milk with the current Missouri productivity. The embodied energy for milk tank is negligible; the steel mass of a small tank of 1000 l is around 265 kg, that is 2516 MJ, or just 168 MJ year^{-1} assuming a lifetime of 15 years which is equivalent to $2 \cdot 10^{-4}$ MJ kg^{-1} of milk.

2.3. Energy for fertilizers, pesticides and seeds

The various nitrogen products employed in agriculture are shown in Table 4. In the US the combination of nitrogen fertilizers used is equivalent to a weighted average energy of 43.14 MJ kg^{-1} of nitrogen. The energy input for ammonia aqueous solution was based on its nitrogen content. The input for UAN 32 Nitrogen solution was computed as a weighted average of ammonium nitrate (45%) and urea (35%). The average energy input in nitrogen fertilizer for Italy is greater (46.57 MJ kg^{-1}) owing to the larger use of urea, which is the most energy intensive fertilizer.

The specific energy inputs reported in the sixth column of Table 4 are the most recent estimates. For nitrogen fertilizers these inputs decreased appreciably in the last decades owing to the increased energy efficiency in the production process of ammonia (Stout, 1991). The value of 78 MJ kg^{-1} reported by Helsel (1992) and used by Pimentel and Pimentel (2008) should therefore be considered out of date.

For phosphate, potash and lime the values of 15.8 MJ kg^{-1} P_2O_5, 9.3 MJ kg^{-1} K_2O and 2.1 MJ kg^{-1} CaO were used (Jenssen and Kongshaug, 2003, Mortimer et al. 2003, Williams et al. 2006). Typical values for fertilizer use on feed crops were available from FAPRI (2014) for Missouri and from Bortolazzo et al. (2007) for Emilia-Romagna. These values were used as defaults when no other specific information was available from the farms.

No energy was allocated for organic fertilizers, either for cow manure produced on the farms, or for other manure (pig or poultry) purchased elsewhere. Energy used to spread this fertilizer is already accounted in the direct energy consumption.

Energy use for herbicide production is listed in the first column of Table 5 (Green, 1987 and Audsley et al., 2009). Herbicide use intensity in Missouri maize and soybean cultivation is available from the most recent data of the National Agricultural Statistics Service (NASS, 2006) and is listed in the second and third columns of the table. Use of insecticides and fungicides on these crops is negligible.

Total use of chemicals was computed by multiplying specific use by the 1997–2012 average crop areas — 1.2 Mha for maize and 2.0 Mha for soybeans (USDA, 2012b). Despite the different uses of chemicals in the two cropping systems, the weighted average of input energy is almost identical. On a per hectare basis, however energy input is notably higher for maize (4658 MJ ha^{-1}) than for soybeans (2200 MJ ha^{-1}). Obviously, these values reflect the particular use of pesticides in the State of Missouri and might be different in other States or from the national average.

The production of hybrid and genetically engineered seeds is very energy intensive and requires about 104 MJ kg^{-1} of seeds for maize (Patzek, 2004) and 33.4 MJ kg^{-1} of seeds for soybeans (Pimentel and Patzek, 2005). Taking into account the typical Missouri seed density and crop yield (FAPRI, 2014) the specific energy input is 0.30 and 0.76 MJ kg^{-1} of crop respectively.

2.4. Direct energy use

Higher heating values were considered for all fuels: 44.8 MJ kg^{-1} for diesel fuel, 47.3 for gasoline, and 50.3 for LPG. These values reflect the net energy consumed by engines and heaters (E_{net}), while some extra energy must be invested in order to extract, refine and transport the fuel to the point of use (E_{inv}), giving total gross energy consumption as the sum, $E_{gross} = E_{net} + E_{inv}$. Gross energy inputs were considered in this study, since they express the real energy consumption in a cradle to farm gate approach, which is higher than the consumption for the final user. The ratio between E_{gross} and E_{inv} is known as EROI, *Energy Return On Investment* (Murphy et al., 2011). Oil and gas extracted in the United States have a typical EROI of 10 (Hall et al., 2014), so the equivalent gross consumption is obtained by multiplying the net consumption by 1.11 (Egross $= 10\,E_{inv} = 10\,(E_{gross} - E_{net})$ so $E_{gross} = 10/9\,E_{inv}$).

In order to evaluate the gross input equivalent for electrical energy, the contribution to total electric generation by the various renewable and non-renewable sources is needed (electric output, 1st and 4th columns of Table 6). Net input energy (2nd and 5th columns of Table 6) is obtained by dividing the electric output by the efficiency of the thermoelectric processes, which is equal to 38.2%, 41.6%, and 53.6% for Italian coal, oil, and gas respectively (Terna, 2013), and to 32.5%, 32.6% 33% and 44% for nuclear, coal, oil and gas, respectively in Missouri (EIA, 2013a, b). Italian data include imports from neighboring countries, France, Switzerland, Austria and Slovenia (Terna, 2013 and IEA, 2013). Missouri is a net exporter of electricity (EIA, 2013b).

The gross input takes into account the energy invested to produce the fuels and the renewable energy equipment (3rd and 6th column

Table 4
Determination of the average value of nitrogen fertilizer input energy according to the different uses of products in USA and Italy.

N fertilizer		N mass fraction	2001—2011 average use [a]	N content	Input energy [b]	Total energy
		%	Mt	Mt	MJ kg^{-1} N	PJ
USA	Anhydrous Ammonia	82.24%	3.65	3.00	38.6	115.87
	Ammonia solution	20.00%	0.32	0.06	9.39	0.60
	Ammonium nitrate	35.00%	1.05	0.37	40.6	14.92
	Ammonium sulfate	21.20%	1.12	0.24	42	9.97
	UAN	32.00%	9.58	3.07	44.28	135.73
	Urea	46.62%	4.94	2.30	49	112.85
	Total		20.66	9.04		389.94
	Average				43.14	
Italy	Ammonium nitrate	35.00%	0.107	0.037	40.6	1.52
	Ammonium sulfate	21.2%	0.042	0.009	42	0.38
	Urea	46.62%	0.345	0.161	49	7.89
	Others	32.00%	0.085	0.027	42	1.14
	Total		0.580	0.234		10.94
	Average				46.57	

Sources:
[a] USDA (2013), ISTAT (2014).
[b] Jenssen and Kongshaug (2003), Mortimer et al. (2003), Williams et al. (2006).

of Table 6). Gross input energy is obtained by multiplying each net input by $\varepsilon/(\varepsilon - 1)$, where ε is the EROI of the source. EROI values are equal to 10 for oil and gas, 80 for coal, 14 for nuclear, 84 for hydroelectric, 18 for wind and 10 for photovoltaic (Hall et al., 2014).

One megajoule of electricity for the end user is therefore equivalent to a gross input of 3.04 MJ of primary energy in Missouri and 1.92 MJ in Italy. Primary energy consumption is higher in Missouri since electricity is produced mainly through low efficiency coal plants and its renewable contribution is almost negligible (2.5%). In contrast, in Italy the contribution of renewable energy is high (33.5%), so there is less need to use low efficiency production systems.

2.5. Energy input for maize, soybeans, forages and byproducts

Energy input for the most important animal feeds purchased by the farms on the market was computed using the methods previously described, assuming standard fertilizer and pesticide application rates (FAPRI, 2014 and NASS, 2006). The results are shown in Fig. 3. Note that these energy inputs are pronouncedly lower than those reported by Pimentel and Pimentel (2008) for corn, soybeans and forages due to our more accurate estimate of nitrogen process energy (see Section 2.3) and more recent assumptions regarding fuel consumption and machinery allocation.

Soybean has the highest energy intensiveness mainly because of its lower yields. Maize is the second highest due to the higher energy cost for nitrogen fertilizers. Forage requires lower energy inputs despite lower yields and higher requirements for structures, because it does not require pesticides.

Only a small fraction of soybean production is directly used as feed, since most of the product is fed to animals as soybean cake and soybean hulls, after the extraction of oil destined for human consumption. Processing soybeans yields 79.2% cake, 18.7% oil and 2.1% hulls (based on the average of US processors from 2000 to 2011, FAOSTAT, 2015), with an input of 3.89 MJ kg^{-1} of soybeans (Kim and Dale, 2002) that sums up to 6.63 MJ kg^{-1} if cultivation energy is included (Fig. 3). Since mass was used as the basis for allocating energy input among the byproducts, this value is the same for the three byproducts (cake, oil and hulls).

Gluten maize feed and gluten maize meal, which are used as protein supplements in animal feed, are byproducts of the wet milling process for bioethanol production.

Maize processing requires 8.76 MJ kg^{-1} of maize and yields 50.8% ethanol, 34.5% gluten feed, 8.1% gluten meal and 6.6% oil (Kim and Dale, 2002). It was assumed that the agriculture and process energy of

Table 5
Average energy input for herbicides for maize and soybean cultivation in Missouri. Based on 1997–2012 average crop areas: 1.2 Mha of maize and 2.0 Mha of soybeans. (USDA, 2012a, b, c and d).

Herbicide type	Energy input[a]	Specific use[b]		Total use		Total energy expenditure	
		Maize	Soy	Maize	Soy	Maize	Soy
	MJ kg^{-1}	kg ha^{-1}	kg ha^{-1}	kt	kt	TJ	TJ
Acetochlor	278	2.44		2.91		810	
Imazaquin	518[*]	2.28		2.71		1406	
Cyanazine	221	2.28		2.71		600	
Metolachlor	276	1.92	2.28	2.29	4.55	631	1257
Atrazine	208	1.57		1.87		389	
Dimethenamid	519[*]	1.15		1.38		715	
Simazine	226[*]	0.99		1.18		266	
Glyphosate	474	0.78	1.02	0.94	2.04	444	967
2,4D	107	0.49	0.58	0.59	1.17	63	125
Bromoxynil	302[*]	0.28		0.33		101	
Clopyralid	432[*]	0.11		0.13		58	
Mesotrione	691[*]	0.09		0.11		74	
Trifluralin	171		1.01		2.02		345
Pendimethalin	421[*]		0.99		1.97		831
Paraquat	460		0.76		1.53		702
Pyraclostrobin	702[*]		0.12		0.25		173
Total		14.38	6.76	17.16	13.52	5557	4400
Average input energy in Missouri (MJ kg^{-1} active ingredient)						323.90	325.32

Sources:
[a] Green (1987).
[b] NASS (2006).
[*] Audsley et al. (2009).

Table 6
Electrical energy sources in Missouri and Italy for 2013: electric output, thermal net input for non-renewable sources and gross input taking into account EROI.

Energy source	Missouri[a]			Italy[b]		
	Electric output	Net input	Gross input	Electric output	Net input	Gross input
	PJ	PJ	PJ	PJ	PJ	PJ
Renewables	8.6	8.6	9.1	417.6	417.6	439.9
Nuclear	30.1	92.5	99.6	64.2	204.2	219.7
Coal	274.3	839.4	850.0	246.7	646.5	654.7
Oil	0.2	0.7	0.8	20.2	49.2	54.7
Gas	15.8	36.0	40.0	137.4	821.3	912.9
TOTAL	329.1	977.2	999.5	1186.1	2139.0	2281.9
Input/output			3.04			1.92

Sources:
[a] EIA, 2013a.
[b] IEA, 2013 and Terna, 2013.

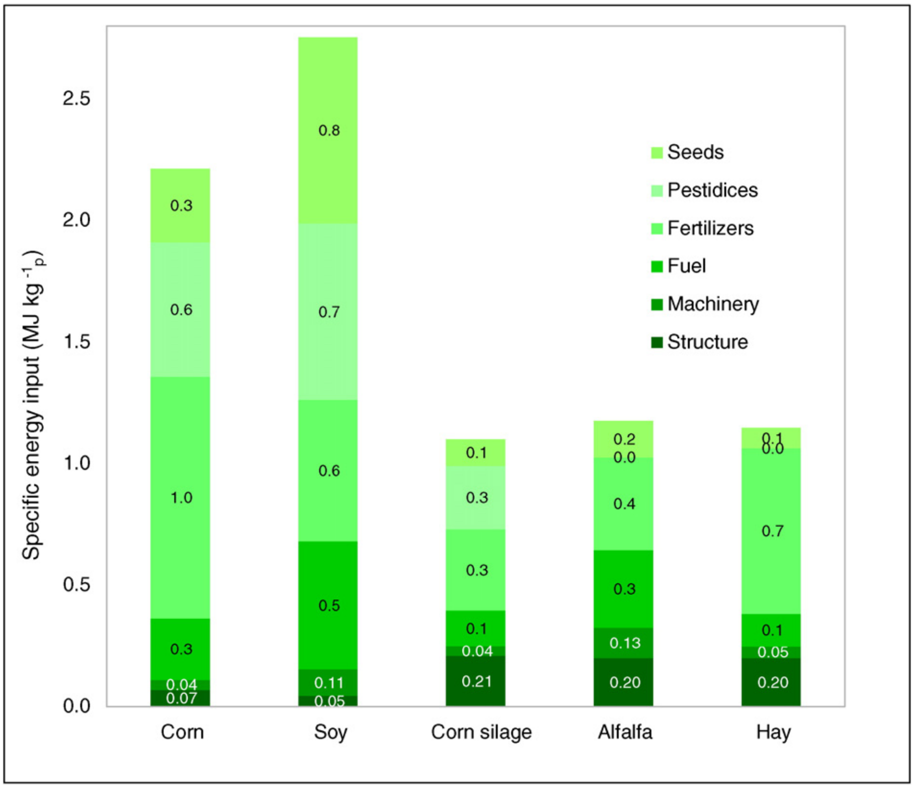

Fig. 3. Energy input intensity for the cultivation of crops and forages used for animal feed.

10.96 MJ kg^{-1} (8.76 + 2.21 of Fig. 3) is equally embodied in ethanol and gluten feed/meal. *Dried distillers grain and solubles* (DDGS) are a byproduct of the dry milling process for bioethanol production. In this case maize processing requires 8.46 MJ kg^{-1} and yields 52.1% of ethanol and 47.9% of DDGS (Kim and Dale, 2002). The total agriculture and process energy of 10.67 MJ kg^{-1} (8.46 + 2.21 from Fig. 3) was equally attributed to all byproducts.

The fourth commodity used in animal feed is brewers' spent grains, a byproduct of the beer industry. Barley is the most important cereal used for beer production and requires about 2.8 MJ kg^{-1} for its cultivation (Khan et al., 2010), while the brewing process counts for another 2.13 MJ kg^{-1} of barley (Kløverpris et al., 2009), for a total of 4.93 MJ kg^{-1}.

For every kg of barley used in the process, 0.71 kg of spent grains, sharps and sprouts are produced and only 0.29 kg end up in beer (Kløverpris et al., 2009). Embodied energy was allocated based on mass.

2.6. Energy for feeding replacement heifers

Milk cows are usually replaced by a new generation and sold for meat, due to a lower productivity, a reduction of pregnancies or illness. The number of lactations per cow usually ranges from 2 to 3 in larger industrial farms and from 4 to 6 in smaller traditional ones.

Energy input for the breeding of replacement heifers differs between two periods: (*a*) milk feeding for the first 60 days and (*b*) weaning and growth until first lactation.

(a) During the milk-fed period, calves are fed a daily average ration of 3.5 kg of milk or milk replacer (ranging from 2.5 kg d^{-1} at birth to 4.5 kg d^{-1} at the beginning of weaning, Wattiaux, 1999). When farms use their own milk, no energy cost was allocated as it is already subtracted from the production data.
If instead farms are buying milk or replacer, an average energy cost of milk production and processing was attributed, assuming that embodied energy is the same in both cases, since replacers are usually made from milk byproducts (assuming mass-based allocation). No data are available for US or Italian milk, so a global average value of 3.4 MJ kg^{-1} was calculated by averaging 22 studies (references are reported in Section 4.4). Assuming a milk-fed period of 60 days, the total energy input is $E_M = 0.7$ GJ.

(b) During the weaning and growth period, the average specific input of a typical feed is estimated to be 4 MJ per kg of dry matter (see Table 7 for details).
The daily dry matter mass intake of heifers was calculated using the data of Zanton and Heinrichs (2008) as

$$m(t) = 1.22 \cdot 10^{-2}\, t + 1.34 \left(\mathrm{kg_{DM}\ d^{-1}}\right) \tag{2}$$

Table 7
Typical ration for heifers from weaning to calving and embodied energy in the various feed products.

Feed products	Diet composition at[a]		Specific input energy	Input energy in mixture	
	4 months	23 months		4 months	23 months
	%	%	MJ kg^{-1} DM	MJ	MJ
Hay	8.0%	15.0%	1.19	0.10	0.18
Corn silage	12.0%	25.0%	3.14	0.38	0.79
Corn	40.5%	31.25%	2.47	1.00	0.77
Soybean meal	9.0%	0.0%	7.46	0.67	0.00
DDGS	7.0%	15.0%	11.99	0.84	1.80
Wheat middlings	10.0%	10.0%	0.36[b]	0.04	0.04
Molasses	10.0%	0.0%	6.84[b]	0.68	0.00
Urea	0.5%	0.75%	49	0.25	0.37
Lime	3.0%	3.0%	2.1	0.06	0.06
Total	100.0%	100.0%	–	4.01	3.99

Sources:
[a] Zanton and Heinrichs (2008).
[b] Davulis and Frick (1977) and Section 2.4.

and the related embodied energy is.

$$e(t) = 4.96 \cdot 10^{-2}\, t + 5.36 \left(\mathrm{MJ\, d^{-1}}\right) \qquad (3)$$

where t is the heifer's age (days) assuming that weaning starts at 60 days. The total feed embodied energy from weaning to calving is then the integral of (3) evaluated between weaning time and calving time T_C:

$$e(T_C) = 2.48 \cdot 10^{-2}\, {T_C}^2 + 5.36\, T_C - 402.60\ (\mathrm{MJ}). \qquad (4)$$

For $T_C = 24$ months, the total embodied energy is on the order of 16 GJ for a total feed mass of 4 tons.

This energy input was used for every cow (milking and dry) in the herd; in order to allocate this value to one year; it was multiplied by the *herd turnover rate* r, which is the number of cows that must be replaced each year owing to sales, illnesses or deaths:

$$E_{cow}(T_C, r) = r\, [E(T_C) + E_M]. \qquad (5)$$

Eq. (5) indicates that the yearly fraction of the total input for feed that should be allocated is equivalent to r.

3. Results

Fig. 4 shows the energy input for milk production for the analyzed farms. Strikingly, energy costs in Emilian farms (2.8 ± 0.3 MJ kg^{-1} ECM) is about 35% less than Missouri farms (4.4 ± 0.7 MJ kg^{-1}), with $p = 0.03$. This difference is because Italian farming practices involve (*i*) smaller daily rations for cows and greater use of alfalfa, which combine to reduce the energy requirements for feed production (−28%), (*ii*) lower energy inputs for heifers (−20%), and (*iii*) lower fuel consumption (−52%). This latter factor is related to the fact that smaller tractors are used on Italian farms, on average 70 kW, compared to the 90 kW tractors on Missouri farms.

In Missouri, energy input of *grain based farms* ranges from 5 to more than 6.5 MJ kg^{-1}. For farm G1, over half of the energy cost is related to feed, since the farm purchases all its feed, with no self-production. At the same time, it avoids fuel and fertilizer costs linked to crop and forage production. In contrast, despite its greater reliance on machinery due to its small scale (30 animals), G2's lower feed-related energy inputs keep the total energy footprint 1.0 MJ lower than that of G1.

Forage based farms (F1 and F2) show very similar results, despite their different sizes (95 versus 547 cows). The energy footprint per cow is about 75% lower than in grain based holdings, since the reliance on pasture allows savings in feed (silage is only fed to dry cows in winter), fuel and structure/machinery inputs (lower tractor inputs and no barns, since animals are always in the fields). Although this reduction is partially compensated by the lower animal productivity (about 45% less milk per cow), the inputs for F1 and F2 per kg of milk (3.4 MJ kg^{-1}) are still about 40–50% lower than in G1 and G2.

The results for *organic* farms present more variance, since inputs range from less than 2 to 6 MJ kg^{-1}. The reason for this difference is

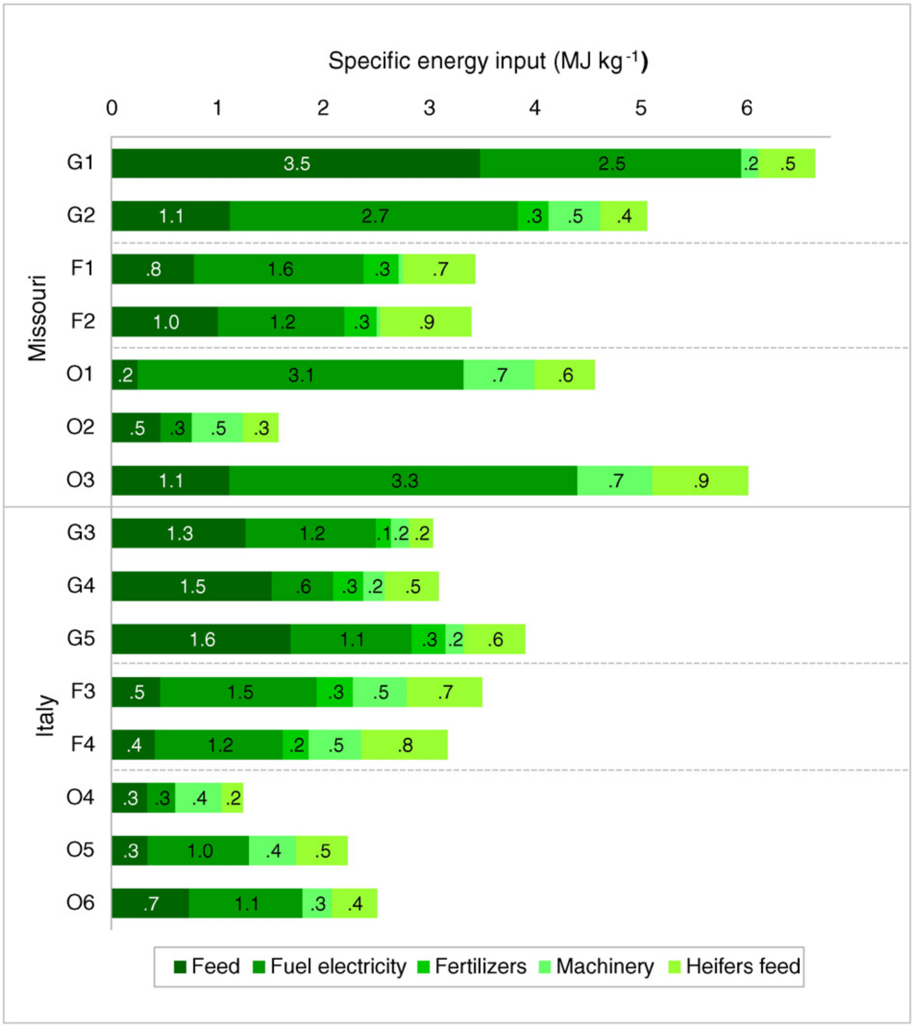

Fig. 4. Energy input per kg of ECM for the surveyed farms.

that, although the milk produced by O1, O2 and O3 is equally certified organic, the three farms use very different practices. Farm O2 has the lowest energy input thanks to a combination of cow pasturing, no use of electricity, no use of tractors and a high number of lactations per cow, which lowers the cull index. The 7 horses used to pull the tiller are roughly equivalent to the input energy of one tractor, while all other farms use more than one tractor for their operations. Farms O1 and O3 have higher costs for fuel, mainly because they require longer times for organic fertilizer application.

In Emilia-Romagna, energy input in *grain based farms* varies between 3 and 4 MJ kg^{-1}, with only slight differences between G3, G4 and G5. The PV panels and a biogas plant cover all electricity requirements of farm G4, lowering its direct energy cost. Indeed, the integration of renewable energy in the food sector, especially bioenergy from byproducts, is quite relevant in the region and could offer major benefits when displacing fossil energy consumption (De Menna et al., 2015a; Cavicchi et al., 2014). Farm G3 has a very low value for heifer feed since it its heifer first calve at 14 month of age, while the average regional value is around 24 months.

Forage based farms F3 and F4 have slightly lower energy footprints than grain based farms, but the difference is not relevant, because it depends mainly on the lower amount of grain in the daily rations, while the general organization of the farm is similar. Therefore, the lower inputs for feed are offset by higher values for fuel, machinery and heifer feed, due to the small size of these farms.

The results for organic farms are very similar, ranging between 1.25 and 2.5 MJ kg^{-1}. These low values are due to their zero cost for fertilizer, which is produced on the farm, and for feed, since pastures require lower inputs.

The outstanding performance of farm O4 (only 1.35 MJ kg^{-1} of milk) is due to the following factors: few mechanical operations with only one tractor (low machinery and fuel costs), extensive field farming with manure fertilization, and a higher number of lactations and thus a very low culling index. Farms O5 and O6 have slightly higher energy consumption levels because of greater reliance on machinery and fuel, but their performance is still on the lower end of the range, both for Missouri farms and non-organic Emilian farms.

4. Discussion

4.1. Effect of feed composition

Feed composition has a strong influence on the energetic cost of milk, as can be seen when the specific energy input for feed and fertilizers is plotted against the fraction of grain in the daily rations of cows (Fig. 5). The analysis is limited to Emilian farms, where the exact amount of forage is known, being fed as hay. In all Missouri's forage based farms, grass is consumed in situ, so it can only be estimated.

The correlation is quite significant ($R^2 = 0.85$), suggesting that energy consumption increases in proportion with the share of maize, barley, sorghum or soy in the diet. Specifically, every 10% increase in grain consumption leads to an average increase in energy input of 0.35 MJ kg^{-1} ECM. This is due to the fact that grains require more input energy than grass forages.

As noted, Emilian farms are more energy efficient than Missouri farms, since they can achieve almost the same milk productivity at about half the energy cost. The average Emilian milk productivity (8800 ± 1980 kg yr^{-1} per cow) is higher than in Missouri (7,016 ± 2,700 kg yr^{-1} per cow), but the difference is not statistically significant ($p = 0.17$) given the small number of observations. The difference in energy input between the two groups of farms (Emilia at 2.8 ± 0.3; Missouri at 4.9 ± 0.8) is, on the other hand, statistically significant at the 5% level ($p = 0.04$).

No definite relationship was observed between specific energy consumption and herd size.

4.2. Energy input and productivity

Cow productivity increases almost linearly with the total energy input, as can be seen when the productivity (in kg ECM yr^{-1} per cow) is plotted against the total energy input on a per cow basis (Fig. 6).

On average, in Italy every increase of 1 GJ per cow results in a rise in milk productivity of 149 kg yr^{-1} per cow compared to 115 kg yr^{-1} per cow for the US. Thus a reduction in milk productivity by this amount would lead to energy savings of 1 GJ per cow (equivalent to about 24 kg of oil).

Although suggesting a productivity reduction may seem unusual, since its increase has been promoted for decades, it is worth mentioning that according to FAO, Food and Agriculture Organization of the United Nations (2009) estimates, in the USA about 18.6% of all the milk produced is wasted, mainly at the household (13.5%) and farm levels (4%), while in Italy the waste is 16%, of which 10% is at the consumption level and 4% at the production level. Waste on the farm is mainly caused by cow mastitis, which is more likely to occur in cows with a higher productivity in previous lactations (Fleischer et al. 2001). Thus, on average, every year 770 to 1550 kg of milk per cow is wasted in the US and 1000 to 2000 kg in Italy, the higher waste occurring in correspondence to higher milk productivity. Consequently, the associated energy wasted is about 7 to 13 GJ per cow in the US and 5 to 9 GJ per cow in Italy. This estimate includes only energy wasted at the farm level, but more energy waste occurs as food is lost or wasted during processing, distribution, and consumption (De Menna et al., 2015b, Pagani et al., 2015).

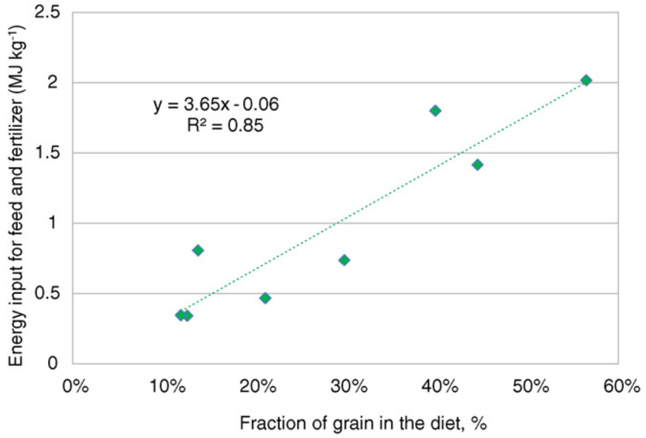

Fig. 5. Correlation between fraction of grain in the diet and energy input for feed and fertilizers for farms in Emilia-Romagna.

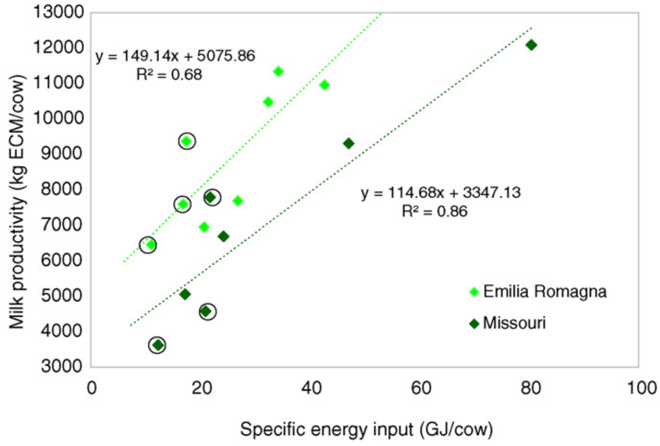

Fig. 6. Correlation between total energy input per cow and cow productivity for farms in Missouri and Emilia. Organic farms have circled dots.

Table 8
Average input energies for different farm types. % differences are related to grain based farms or to Missouri (last column). Significance levels are: ns, not significant; (*) $p < 0.1$; (**) $p < 0.05$.

(a) Average energy per kg of ECM

Farm type	Missouri (M)	Emilia-Romagna (ER)	(ER-M)/M
	Energy input MJ kg^{-1}	Energy input, MJ kg^{-1}	%
Grain based (G)	5.85 ± 0.79	3.34 ± 0.28	−43.0% (**)
Forage based (F)	3.42 ± 0.02	3.24 ± 0,26	−5.3% (*ns*)
Organic (O)	4.05 ± 2.26	2.0 ± 0.38	−50.8% (*ns*)
(F-G)/G	−41.6% (*)	−2.9% (ns)	–
(O-G)/G	−30.8% (*ns*)	−40.2% (**)	–
(O-F)/F	+18.5% (*ns*)	−38.4% (*)	–

(b) Energy per animal (GJ/cow)

Farm type	Missouri (M)	Emilia-Romagna (ER)	(ER-M)/M
	Energy input GJ per cow	Energy input, GJ per cow	%
Grain based (G)	63.7 ± 16.6	36.4 ± 3.1	−42.8% (*)
Forage based (F)	20.1 ± 2.9	24.8 ± 4.1	+18.3% (*ns*)
Organic (O)	23.3 ± 4.6	15.1 ± 2.,0	−17.4% (*ns*)
(F-G)/G	−68.5% (*)	−34.7% (*)	–
(O-G)/G	−71.2% (**)	−58.4% (**)	–
(O-F)/F	−8.8% (*ns*)	−36.3% (*)	–

Reduction of this waste through specific policy and education measures, could also achieve a considerable decrease in energy waste.

4.3. Grain, forage or organic: which is better?

The different American and Italian farm practices are reported in Table 8 (a) and (b) in terms of specific energy per kg of ECM and per cow, respectively.

Results are quite different between the two countries. In Missouri, the surveyed forage based farms were more energy efficient than grain based, consuming 41% less energy per kg of ECM ($p = 0.09$). Inputs of organic farm input were 10% lower than grain based, but the difference wasn't statistically significant.

The same can be said for the comparison between organic and non-organic forage based farms; the average consumption of the former is 15% higher but it's not significant.

This difference in performance can be explained by the fact that the surveyed organic farms in Missouri have dissimilar practices regarding feed, fuel and fertilizer use, so the sample produces a higher variance. Forage based farms are much more homogeneous, so their lower input is statistically significant.

In Emilia-Romagna, in contrast, organic farms were more energy efficient, with an energy saving of about 40%, compared to both grain fed and grass fed farms. The difference is significant in both cases ($p = 0.05$ and $p = 0.1$, respectively). Non organic grain and grass fed farms don't differ significantly. Organic farms have comparable practices and lower energy inputs, so the difference is significant both with respect to non-organic grain and forage based farms. Grain and organic Emilian dairy farms have lower inputs than their comparable farms in Missouri. No significant difference was found on forage based farms.

4.4. Renewable energy production

Among the surveyed farms, only three were equipped with photovoltaic panels on rooftops, with installed power ranging from 20 to 700 kW, all located in Italy. In all cases, the production was more than sufficient to cover all electrical energy consumptions related to farm activities and represented a significant share of the total energy use (see Table 9). Farm G4 produced enough electrical energy for its own use with enough surplus to satisfy the average household consumption of more than 800 people.

Farm G4 is also equipped with a biogas plant fed with cows' manure. A manure mass of 9600 t year^{-1} produce about 170,000 Nm^3 of biogas, which is used to feed a combined heat and power generator, with 403 kW and 310 kW of thermal and electric power, respectively. As other byproducts that can be used for anaerobic digestion, manure avoids the land use impacts related to biogas plants fed with energy crops (De Menna et al. 2016). The plant works for approximately 7200 h a year, with a production of about 18500 GJ of electricity, that could satisfy the domestic energy consumption of nearly 17,000 people.

The main drawback of on-site use of biogas for cogeneration is the waste of most of the heat produced, since the thermal consumption of farms is usually a rather small fraction of the available thermal energy from the digester. The possibility of using the heat for a district heating system is also limited by the distance of farms from town and villages (Balsari and Dinuccio, 2011). In contrast, biogas has good potential as fuel for tractors (Coimbra-Araùjo et al., 2014) or general transportation (Patrizio et al., 2015).

For farm G4, the digestate product after the extraction of biogas amounted to about 8,500 t, that could be used as fertilizer with the same quantity of nutrients as the original manure (Möller and Müller, 2012), but with an increased quality and biological availability (Holm-Nielsen et al., 2009).

4.5. Comparison with the literature

Table 10 reports the results of 25 different analyses on energy input in milk production. Reported indicators cover the range of values found in the present analysis. For both conventional and organic farms, the average and standard deviation values are not significantly different from the values of the present work.

In contrast, a significant difference ($p < 0.01$) can be found between the reported indicators for conventional and organic milk, since on average the input energy for the organic product is 34% lower than for conventional production. Energy inputs greater than 5 MJ kg^{-1} of milk production reported in Table 6 are from farms that use a high level of grain in their feed rations, ranging from 63% (Grönroos et al., 2006) to 75% (Hospido et al., 2003) to 87% (Thomassen et al., 2008). This result is consistent with the results of all Emilian farms (Fig. 5).

On the other hand, studies that reported low energy consumptions were related to forage based farms (Haas et al., 2001; Wells, 2001) or to farms with limited amounts of grains in the cow rations (22% in Refsgaard et al., 1998, 40% in Mikkola and Ahokas, 2009), which is consistent with the findings on Missouri farms.

5. Conclusions

The comparison of dairy farming systems in Emilia-Romagna and Missouri provide useful insights in terms of energy saving strategies for this sector. Specifically, results indicate that a potential 40% reduction in the overall energy input could be achieved by shifting to organic farming and following some of the practices of Emilian dairy farms.

Important saving could also be obtained by switching to forage based farming, as in the case of the dairy farms observed in Missouri. In systems where a full conversion to organic or pasture based farming is not feasible, a reduction in the amount of grain in the daily rations and

Table 9
Photovoltaic energy production on some farms.

Farm	Power (kW)	Production factor	Energy (GJ/y)		% of electricity use	% of total use
		kWh/kW$_p$	Production	Use		
G4	690	1280	3180	274	1160.4%	19.3%
O5	19	1280	88	83	105.5%	13.6%
O6	40	1290	229	154	148.7%	6.5%

The production factor is estimated according to PVGIS (2012) and Huld et al. (2012)

Table 10
Literature values for conventional and organic milk input energy (MJ kg^{-1}).

Source	Country	Conventional Farms		Organic Farms	
		Number	Energy	Number	Energy
Eide (2002)	Norway	3	4.47		
Refsgaard et al. (1998)	Denmark	17	3.34	14	2.16
Cederberg & Mattson (2000)	Sweden	1	3.55	1	2.51
Grönroos et al. (2006)	Finland	–[*]	6.4	–[*]	4.4
Mikkola & Ahokas (2009)	Finland	–[*]	3.2		
Frorip et al. (2012)	Estonia	1	5.4		
Thomassen et al. (2008)	Netherlands	10	5	11	3.1
Iepema & Pijnenburg (2001)	Netherlands	3	3.7	3	2.4
O'Brien et al. (2012)	Ireland	1	3.8	1	2.3
Upton et al. (2013)	Ireland	22	2.37		
Meul et al. (2007)	Belgium	–[*]	4.26		
Kraatz (2012)	Germany	–[*]	3.5		
Haas et al. (2001)	Germany	2	2.7	2	1.2
Hospido et al. (2003)	Spain	2	6.0		
Koknaroglu (2010)	Turkey	91	5.0		
Wells (2001)	New Zealand	96	2.02		
Hartman& Sims (2006)	New Zealand	62	3.9		
Smil (2008)	USA	–[*]	6		
Present study		9	4.0 ± 1.1	6	3.0 ± 1.7

[*] These studies used parameters at national or regional level with no field analysis.

the introduction of higher quantities of alfalfa would reduce energy consumption.

Policy actions stimulating the reduction of the amount of milk wasted along the food supply chain would have a positive cascading effect by reducing the needed production of milk and thus the energy input at the agricultural level.

Energy efficiency intervention strategies should promote a sustainable agricultural mechanization; less powerful tractors often ensure fuel savings. For instance, the average milk production in Emilia-Romagna is higher than in Missouri despite the lower usage of mechanical power.

Besides marginal efficiency gains, further research should be focused on the reduction of farming dependency on fossil fuels. The increased and integrated use of renewable energy sources could lead to a transition to low carbon farms, driven by locally available resources such as biogas energy from manure, wind energy in Missouri, or hydroelectric energy in Emilia Romagna.

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