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A partial life cycle assessment approach to evaluate the energy intensity and related greenhouse gas emission in dairy farms

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Abstract

Dairy farming is constantly evolving towards more intensive levels of mechanization and automation which demand more energy consumption and result in higher economic and environmental costs. The usage of fossil energy in agricultural processes contributes to climate change both with on-farm emissions from the combustion of fuels, and by off-farm emissions due to the use of grid power. As a consequence, a more efficient use of fossil resources together with an increased use of renewable energies can play a key role for the development of more sustainable production systems. The aims of this study were to evaluate the energy requirements (fuels and electricity) in dairy farms, define the distribution of the energy demands among the different farm operations, identify the critical point of the process and estimate the amount of CO_2 associated with the energy consumption. The inventory of the energy uses has been outlined by a partial Life Cycle Assessment (LCA) approach, setting the system boundaries at the farm level, from cradle to farm gate. All the flows of materials and energy associated to milk production process, including crops cultivation for fodder production, were investigated in 20 dairy commercial farms over a period of one year. Self-produced energy from renewable sources was also accounted as it influence the overall balance of emissions. Data analysis was focused on the calculation of energy and environmental sustainability indicators (EUI, CO_2-eq) referred to the functional units. The production of 1 kg of Fat and Protein Corrected Milk (FPCM) required on average 0.044 kWh_{el} and 0.251 kWh_{th}, corresponding to a total emission of 0.085 kg CO_2-eq). The farm activities that contribute most to the electricity requirements were milk cooling, milking and slurry management, while feeding management and crop cultivation were the greatest diesel fuel consuming operation and the largest in terms of environmental impact of milk production (73% of energy CO_2-eq emissions). The results of the study can assist in the development of dairy farming models based on a more efficient and profitable use of the energy resources.

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Introduction

Energy consumption, water utilization and environmental impact are becoming the major issues in the agro-food sector that is called to respond adequately to the climate change problems. Agricultural and livestock activities are important sources of primary greenhouse gases (GHGs). These sectors have been estimate to contribute for about 10-12% to global anthropogenic GHG emissions (Grosson *et al.*, 2011; Smith *et al.*, 2007). Furthermore, agriculture is responsible of indirect emissions in other industrial sectors which supply the resources consumed in the agricultural processes (IPCC 2006). The usage of fossil energy in agricultural processes contributes to climate change both with on-farm emissions from the combustion of fuels, and by off-farm emissions due to production and transport to the farm of agricultural inputs (West *et al.*, 2010). As a consequence, a more efficient use of fossil resources together with an increased use of renewable energies can play a key role for the development of more sustainable production systems.

The methodology that is internationally applied to assess the global impact associated to production activities or products is Life Cycle Assessment (LCA). LCA allows to analyse all the inputs and outputs of a system to estimate the potential environmental impact of a product or service through its life cycle (UNI EN ISO 14040-44 2006). The stages of LCA are: goal and scope definition, inventory analysis, impact assessment an interpretation of results. The system boundaries are used to define the limit of the study and results of LCA are expressed for functional unit of product. All data concerning the use of resources, the energy requirements, the emissions and the products resulting from each process are collected during the inventory analysis. As the impact categories and the level of detail of the analysis can be chosen and specified, the LCA procedure can be tailored to the goals of the study.

The aims of this study were to evaluate the energy requirements in dairy farms, define the distribution of the energy demands among the different farm operations, identify the critical point of the process and estimate the amount of CO_2 associated with the energy consumption. The study, based on a simplified LCA approach, involved 20 dairy conventional farms over a period of one year, half of which have a photovoltaic system for electricity generation.

Materials and methods

This work is a part of a larger research project (*Dairy Carbon Footprint-Filiera AQ*) involving 285 dairy farms located in the centre and south Italy and which aims to assess the potential environmental impact of milk production at farm level. A sample of 20 dairy farms, located in the Arborea area (Sardinia, Italy) are analysed in this study to quantify the fossil energy flows and the carbon dioxide equivalent (CO_2-eq) emissions associated to farming activities.

Data inventoried in each farm, related to year 2011, include general information such as herd size, animal categories, land used, milk quality and production, and a detailed description of cultivated crops, farm structures, equipment and machinery.

Detailed statistics of the monthly energy flows, such as consumption bills of fuels and electricity and the self-produced energy from photovoltaic (PV) generators, were recorded.

The overall data were structured in a data base created on Microsoft Excel. Further calculations were performed to determine sustainability indicators, such as Energy Utilization Indices (EUI) and CO_2-eq emissions referred to functional units (cows, kg of Fat and Protein Corrected Milk -FPCM), that can be compared to literature data.

A detailed energy auditing was performed to allocate the energy consumptions among the different farm activities. All the electrical appliances operating at farm level have been inventoried, reporting the power of each equipment and its usage time (hours per day, days per year) to obtain the annual electricity consumption. Additionally, comparison between the audit data and the electricity bills were performed to evaluate the conformity of the results.

The following farm activities have been detailed:

Lighting: type and power of lamps, as well the illumination time, were collected from barns and farm's facilities

Ventilation and misting: used to lower the air temperature in cowsheds and reduce cow's heat stress during the warm season. These equipment run only when the temperature is above 20-25°C, and the usage time was obtained from the manager interview.

Brushing: 65% of the farm's sample uses mechanized brush to increase cow's comfort. The system is equipped with an electric motor that allows brush rotation as soon as the cow touches it. Operating time of cow brushing was set at 6 minutes/day per milking cow (DeVries, 2007).

Milking: the inputs due to the use of vacuum pump, milk pump and air compressor have been summed together to outline the total consumption of the milking operation. Additionally, the presence of a Variable Drive Speed (VDS) system was taken into account when assessing the electrical consumption of the vacuum pump. The VDS device allows reducing the speed of the vacuum pump based on the vacuum level requirement during milking, thus diminishing of 40-50% the electrical consumption. The 60% of the investigated farms were provided of a VDS system. Electrical consumptions of milk pump and air compressor were set as a 4% of the vacuum pump consumption.

Milk Cooling: electrical consumption for milk refrigeration shows high variations due to the presence or not of the pre-cooling system. The following procedure was used to assess the annual energy consumption (RE_{el})of the milk tank:

$$RE_{el} = \frac{m \times c_p \times (t_1 - t_2)}{COP \times \eta \times 3.6} \qquad \left[\mathrm{kWh \cdot y^{-1}}\right]$$

where m (kg · year^{-1}) is the mass of milk, c_p (MJ kg^{-1} °C^{-1}) the milk specific heat value, t_1 and t_2(°C) the initial and final milk temperatures, COP and η are respectively the coefficient of performance and the efficiency of the refrigeration system, 3.6 the conversion factor from MJ to kWh. The electricity required milk cooling is reduced by the use of precoolers which lower the temperature of the milk entering the tank. The magnitude of this reduction depends on the temperature of the cooling media; a decrease of 16°C was set in t_1 value when the pre-cooler was available (30% of the farms).

Water heating: both the milking system and the cooling tank need high volumes of water in order to clean and disinfect all the equipment used during the milking operation. Hot wash water (50÷65°C) was used in 19 farms over 20, while only one used warm water (40°C). Different water heating systems were found during the survey: 85% of the investigated farms were equipped with an electrical water heater and 90% with heat recovery systems (HRS) which recuperate the heat given off by the condenser of the refrigeration circuit. The quantities of hot water produced vary based on the quantity of milk refrigerated.

The following equation was used to assess the energy () related with hot water consumptions:

$$RE_{el} = \frac{m \times c_p \times (t_1 - t_2)}{COP \times \eta \times 3.6} \qquad \left[\mathrm{kWh \cdot y^{-1}}\right]$$

where m (kg · year^{-1}) is the mass of wash water set at 12 kg per milking unit per milking (SCE, 2004) plus 150-200 L per day for the bulk tank, cp (MJ kg^{-1} °C^{-1}) the water specific heat value, t_1 and t_2 (°C) the initial and final water temperatures, η the efficiency of the electric boiler, 3.6 the conversion factor from MJ to kWh. Different Δt values were applied according to the presence/absence of HRS and the final water temperature required.

Water supply: energy consumptions have been split among water pumping, related only to cowshed and parlour water requirements, and irrigation, associated with the water distribution systems. All farms use an irrigation system of cultivated fields, but only 10% of them use water pumping.

Slurry management: energy consumptions are related to all the equipment used for manure removal, storage, and treatment.

Other: this section includes the operations with lower impact on dairy farm energy demands such as water treatment, feed preparation and high pressure cleaning.

Farm fuel consumptions have been grouped in three main processes:

Field operations, related to forage and animal feed production. The overall tasks carried out for crop cultivation were divided into four sections: slurry distribution; soil tillage; sowing; fertilization and treatment; harvesting and storage of the product.

Slurry management, including operations as sewage management and treatment.

Feeding operations, regarding feed preparation and distribution by means of mixer trailers.

To estimate the tractor diesel consumption due to each operation, the usage time of the machinery, the power of the tractor and the fuel consumption at partial load (Q) have been considered. Q was derived from the following equation (Grisso *et al.*, 2004): $Q = (0.22\,X + 0.096) \cdot P_{pto}$ (L· h^{-1}) which considers the rated power of the machinery(P_{pto}, *kW*) and the estimated ratio (*X, decimal*) of the rated power being used during field operations. A value of 0.30 was set for light operations till to a value of 0.65 for the heaviest ones. A conversion factor of 0.835 kg·L^{-1} was then used to transform the equation results in kg of diesel.

The carbon dioxide emission derived from energy uses was calculated multiplying the total consumptions to the following specific emission factors: 0.4103 kg CO_2-eq kWh^{-1} (ISPRA 2011), based on the energy mix used to produce electricity in Italy, and 3.15 kg CO_2-eq kg^{-1}(ENEA 2010) to assess the emission from diesel combustion.

On farm renewable energy production was monitored in 10 farms which produce photovoltaic electricity. The total production of each PV system (kWh·year^{-1}) was analysed to determine the efficiency (kWh per kW$_p^{-1}$) and to assess the reduction of carbon dioxide release into the environment. Per each kWh produced, a net emission factor of -0.3813 kg CO_2-eq was considered, derived from the difference between the index of the Italian energy mix (0.4103 kg CO_2-eq·kWh^{-1}, ISPRA 2011) and the CO_2 emitted during the photovoltaic system production (0.029 kg CO_2-eq·kWh^{-1}, Raugei *ethh al.*, 2009).

Results

The characteristics of the studied farms and the annual energy consumptions are summarized in Table 1. The average herd dimension was 320 heads (range 158-500), of which about 44% are milking cows with an average yearly milk production of 10.1 t per cow. The annual energy requirement accounted for 29,519 kg of diesel fuel and 55,843 kWh of electricity, which approximately correspond to an expenditure of 38,500 € per year.

Expressing the farm energy demand in terms of primary energy, which allows to compare the prevalence of the different energy resources, the diesel fuel accounts for about 70% of the total direct energy consumption at farm level, while the electricity represents the 30%.

The farm average emission of carbon dioxide, due to all energy usages, was 120 t CO$_2$-eq per year that corresponds to 0.085 kg CO$_2$-eq per kg of FPCM. Preliminary results on GHG production from the dairy farms included in the larger study indicate a prevalence of about 9% of the emissions due to fossil energy among the total GHG emissions.

The energy intensity of dairy farms represents the measure of energy efficiency and it is calculated as index of energy used (EUI) per unit of herd size or milk production. For the electricity, the EUI$_s$ resulted 401 kWh per milking cow and 0.044 kWh/kg per FPCM per year. These results are lower than those found in similar studies carried out on European dairy farms. In a French study conducted by L'Institut de l'Elevage (2009) which involved 60 dairy farms (milk yield 7.2 t cow^{-1}·year^{-1}) the EUI was 420 kWh/lactating cow and 0.059 kWh/kg of milk per year. These values are 4.5% higher than the present study in terms of kWh for lactating cows and 25% higher if referred to the unit of milk. Greater values are reported in an Italian study carried out on 60 dairy farms (milk yield 8 t cow^{-1}·year^{-1}) in the Emilia Romagna region (Rossi, 2012): 510 kWh per cow per year and 0.064 kWh per kg of milk per year. A German study (Jäkel, 2003) carried out on 41 dairy farms shows an average EUI of 0.09 kWh per kg of milk, a value that is more than double of the present result. The EUI per unit of milk mirrors the value of 0.05 kWh obtained in a previous study carried on in the same region (Murgia *et al.*, 2008), while the index per cow was much larger (466 kWh per lactating cow). The differences in farm technological levels and in yield per cow affect the energy efficiency indicators. Large productions of milk allows reducing the consumption of electricity per unit of milk sold.

The carbon dioxide emissions associated with the electricity inputs were 176 kg CO$_2$-eq/cow per year and 0.019 kg CO$_2$-eq /kg of FPCM per year.

The annual consumption of diesel was 92 kg per cow, which corresponds to 0.021 kg diesel per kg of FPCM. The annual emissions deriving from these inputs were 289 kg CO$_2$-eq per cow and 0.066 kg CO$_2$-eq per kg of FPCM milk per year. When referred to the cultivated land, these indexes were 396 kg of diesel·ha^{-1} and 1248 kg CO$_2$-eq ·ha^{-1} per year.

As shown in figure 1A, milk refrigeration and milking result the most demanding operations in all the dairy farms examined, requiring respectively 23% and 19% of the annual electricity consumption. Also, other processes that affect significantly the electricity requirements are: slurry management (12%), water pumping (11%), irrigation (10%), fan-misting operations (9%) and water heating (8%).

Analysing the diesel fuel consumption associated to farm and field processes (Figure 1B), the feed preparation and distribution represent together the 51% of the total fuel utilization, the land operations related to crop production account for 42% and the sewage management for 7%.

Crop selection of the investigated farms was based on: corn silage (*Zea Mays L.*, 100% of the farms, average cultivation 26±12 ha/farm); grass forage (*Lolium spp.,* 100% of the farms, 25±13 ha/farm); Alfalfa forage (*Medicago Sativa L.*, 55% of the farms, 10±4 ha/farm).

Figure 2 illustrates the total carbon dioxide emission (diesel plus electricity) attributed to each farm operations. Diesel consumption, being responsible of 79% of the total emission from energy usages, represents the most pollutants process of the farms. Feed management represent the 40% of the total carbon dioxide emissions, followed by land operations (33%) and slurry management (6%). The use of electricity accounts for 21% of the total carbon dioxide emissions.

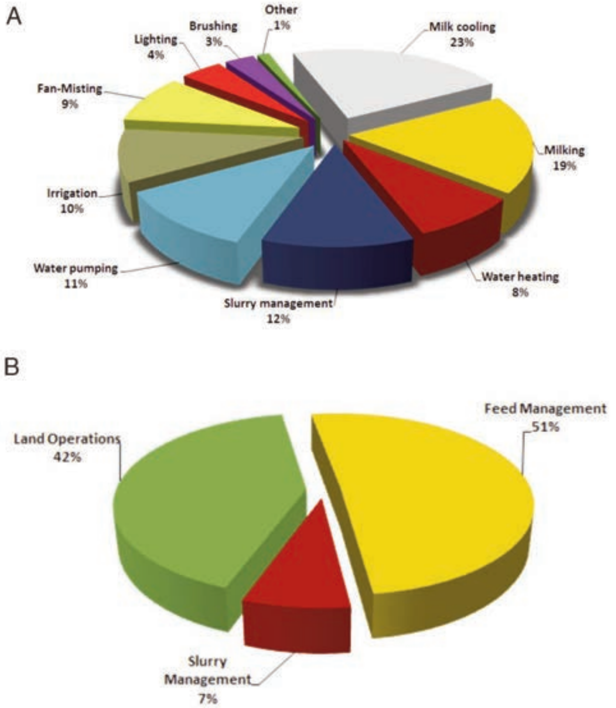

Figure 1. Allocation of fossil energy consumptions (A, electricity; B, diesel) among farm and field operation. Data from 20 dairy farms, referred to an average milk production of 10.1 t.cow^{-1}.year^{-1}.

Table 1. Data summary of the examined farms (N=20)

	Cows (n)	Land (ha)	Milk (t y^{-1})	Diesel (kg y^{-1})	Electricity (kWh y^{-1})
Minimum	158	14	822	12320	31343
Mean	320	47	1412	29597	55843
Maximum	500	95	2678	58394	163893

Photovoltaic energy analysis

The production of energy by PV systems is able to fit the electricity trend demand in dairy farms, as shown in the example of figure 3. The electricity consumption shows peak of request during the summer period due to the higher requests of energy for cooling the cowshed, milk refrigeration and irrigation. Photovoltaic generation follows the natural variability of solar radiation, with higher production during the summer period, peak value in July and minimum during winter months. Therefore PV energy generation can partially supply the demand of electricity during the lower peak of energy generation, but even exceed during the higher peak production. In this case, the surplus of electricity production is injected to the grid and sold.

The study has involved 10 farms which have installed a PV generator integrated on the roof top of the cowsheds. The total PV power installed accounts for 1,122 kWp (corresponding to 0.37 kWp per cow), with an average value of 112 kWp per farm (range 25-250 kWp). The analysis of the PV recorded productions indicates a specific production of about 1,387±14 kWh/kWp per year, which leads to a total electricity generation of 1,559,192 kWh per year.

The PV electricity generation allows to decrease the high peak demand of grid energy during summer period, reducing the emission of carbon dioxide and the cost of the electricity purchased.

Results on yearly base show a positive balance in electricity net production. The surplus of electricity generation was sold, increasing the economic benefits of the farms and reducing the carbon footprint of the milk produced. Final analyses have shown on average a reduction of carbon dioxide emission of 0.023 kg of CO_2-eq per kg of FPCM (from 0.085 to 0.062). The total carbon dioxide reduction was 29,726 kg of CO_2-eq $\cdot y^{-1}$ which represents a 25% decrease of the total amount released by the whole group of farms.

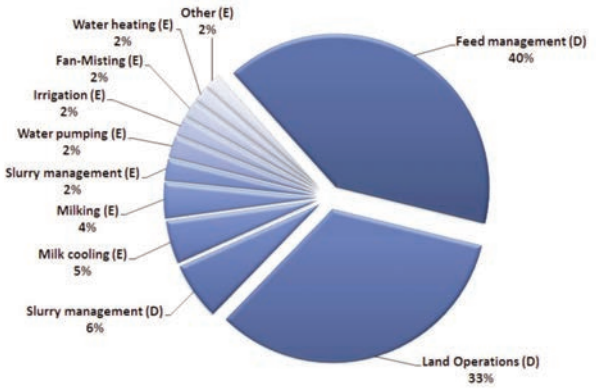

Figure 2. Allocation of GHG emissions from electricity (E) and Diesel (D) to different farm operations.

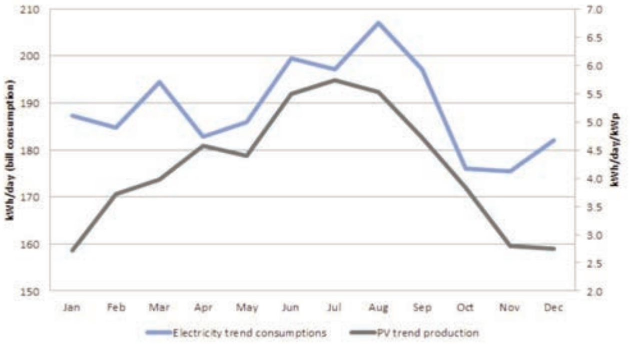

Figure 3. Monthly electricity consumptions and photovoltaic production

Table 2. Annual electricity and diesel consumptions (average ±st.dev) and associated CO_2-eq emissions.

	Electricity		Diesel		
	Consumption (kWhel y-1)	Emission (kg CO2-eq)	Consumption (kg y-1)	Consumption (kWhth)	Emission (kg CO2-eq)
Cow	176 (±74)	78	92 (±21)	1099	289
Lactating Cow	401 (±180)	176	209 (±47)	2496	658
Land (ha)	768 (±358)	338	396 (±123)	4730	1248
FPCM Milk (kg)	0.044 (±0.03)	0.019	0.021 (±0.005)	0.251	0.066

Table 3. Summary of the electricity comparison between farms with PV and without PV system; the results are expressed per year

	No PV system		PV system		
	Consumption (kWh)	Emission (kg CO_2-eq)	Consumption (kWh)	Production (kWh)	Emission* (kg CO_2-eq)
Cow	156	69	196	514	-121
Lactating Cow	349	154	453	1187	-280
Land (ha)	647	285	889	3476	-986
FPC Milk (kg)	0.035	0.016	0.052	0.12	-0.026

*Negative results indicate the avoided emissions due the surplus of PV energy produced

Conclusions

Electricity and fuel consumption in dairy farms represent an important source of GHG emission into the environment. The present study determined the energy requirements for diesel and electricity at farm level, also underlining the critical point where mitigation strategies are needed. Additionally photovoltaic electricity generation was considered as a mitigation strategy to compensate the GHG impact of milk production. PV electricity can also help reducing the demand in dairy farms, especially decreasing the high peak of consumptions.

Electricity requests in the dairy farms involved in the study were mainly due to the operations regarding the milking parlour (milking, milk refrigeration and water heating), which required 50% of the total electricity consumption.

A large number of the investigated farms already use energy saving technologies, such as heat recovery system from cooling tanks (90% of farms), variable speed drive for the vacuum pump (60%) and milk precoolers (30%). Improving energy savings allow to reduce the electricity demand, especially for those equipments that need high electricity input. The estimated electricity emissions of CO_2-eq were 78 kg per cow that correspond to 0.019 kg CO_2-eq per kg of FPCM.

Diesel consumption was assessed for land operations, feed management and slurry management and corresponds to 92 kg of diesel per cow and 392 kg per ha^{-1}. The operations related to animal feeding, as crop cultivation, feed preparation and distribution, require the largest quota of total fuel consumption (42% and 52% respectively). The emissions associated to diesel combustion were 289 kg CO_2-eq per cow and 0.066 kg CO_2-eq per kg of FPCM.

Final results of carbon dioxide emissions from fuel and electricity usage showed that 79 % of the emissions were due to the use of diesel. These results underline the need to focus the mitigation strategies in fuel usage, especially for feed management and land operations.

Reducing electricity and diesel consumption leads to decrease anthropogenic gas emissions into the environment, to reduce costs for the farms and to improve the efficient use of natural resources.

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