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Assessing On-Site Renewable Energy Potential for Parmigiano Reggiano Production

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Abstract: This study investigates the potential of renewable energy integration within the context of Parmigiano Reggiano cheese production. Using real data from dairy plants and farms, advanced approaches for proper energy management are illustrated, including performance indicators for energy benchmarking, the disaggregation of loads for energy efficiency opportunities identification, and the identification of energy demand patterns energy use optimization. The study proposes guidelines for quantifying the potential from solar and biomass energy sources, with a focus on energy self-sufficiency and resource valorization. This is illustrated with regard to a medium-sized dairy farm with a specific energy consumption of 64 kWh/t and 10 kWh/t of milk, respectively. The analysis shows that photovoltaic self-production rate decreases with plant size but can be enhanced to 88% through the integration of energy storage systems. Biogas production can entirely supply the farm's electricity needs, while further valorization of digestate can provide an additional 79% which could be used to meet the energy demands of a corresponding dairy plant (55 kWh/t of electricity and 100 kWh/t of heat). This study demonstrates that state-of-art technologies can substantially cover the energy requirements of dairy operations, and that more advanced systems can support the achievement of full energy self-sufficiency.

Keywords: Renewable energy; Dairy industry; Parmigiano Reggiano; Energy monitoring; Solar energy; Bioenergy

1 Introduction

As in other productive sectors, renewable energy is determinant for environmental analysis of the food industry, as the energy sources influence the sustainability of a product.

This article specifically focuses on the dairy sector, with an emphasis on analyzing the electrical and thermal energy consumption within the production chain of Parmigiano Reggiano, whose manufacture accounts for approximately 20% of the total milk produced in Italy [1]. Besides favoring the resort to clean energy carriers, it is important to harvest as much on-site renewable energy as possible. Renewable plants have typically been installed only for economic purposes without paying attention to self-sufficiency. In the context of a largely renewable grid, attention to variable constraints is mandatory. Maximizing renewable penetration requires valorization of energy-related data. The production of Parmigiano Reggiano cheese involves multiple processing stages, each requiring substantial energy inputs, primarily thermal and electrical energy for milk processing, and diesel fuel for agricultural field operations [2]. A critical aspect of improving energy efficiency in this sector is the comprehensive assessment of thermal and electrical energy consumption across all stages of the supply chain.

In this study, energy demand across the production chain was evaluated through a survey conducted with various stakeholders involved in Parmigiano Reggiano cheese production, specifically dairy farms and processing plants of different sizes. The analysis of monitoring data from real case studies facilitated the assessment of the potential integration of on-site renewable energy sources.

2 Parmigiano Reggiano Production Process

Parmigiano Reggiano is a hard, cooked, and slowly matured cheese produced according to strict regulations defined by a specific set of guidelines from the Consortium [3]. It is made from raw, partially skimmed cow's milk, sourced from animals whose diet consists primarily of forage grown within the designated area of origin; the use of silage is strictly prohibited. In this study, field operations were not specifically included in the energy audit, which instead focuses primarily on energy requirements within barns and dairy processing plants. In the barn, the main electrical energy loads are associated with equipment for animal welfare (particularly cooling systems), feed and manure management, lighting, and the milking process (Figure 1).

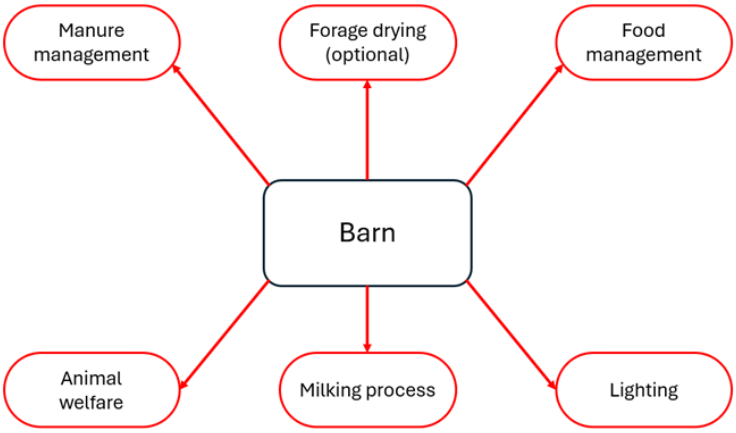

Figure 1. Barn energy users

Some farms may also include a forage dryer. Although this type of equipment is not widely adopted, it enables long-term storage of forage while preserving its high nutritional quality [4]. However, it is also a highly energy-intensive facility.

Once the milk leaves the barn, it is transported to the dairy plant, not always located nearby the barn. This transportation may have a non-negligible impact on diesel consumption for milk delivery. Milk is delivered to the dairy plant twice a day, once in the evening and once in the morning. The various steps of the process of Parmigiano Reggiano cheese production in dairy plants are summarized in Figure 2 [5].

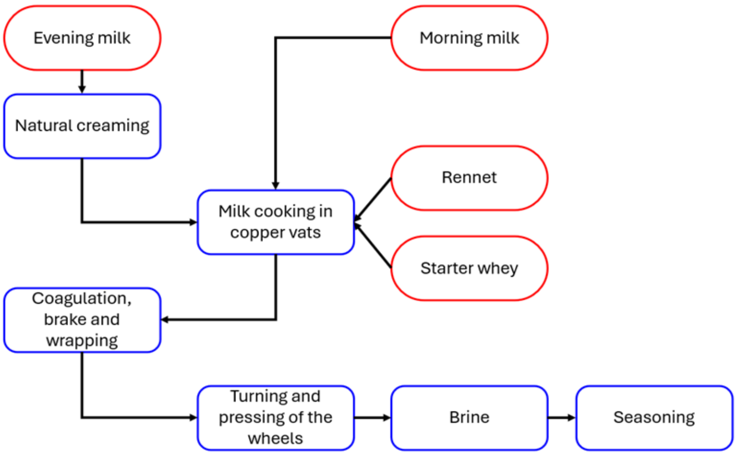

Figure 2. Parmigiano Reggiano processing stages

The evening milk is stored in open vats where it undergoes natural creaming, allowing the fat to separate from the skim portion without centrifugation. The skimmed evening milk is then combined with the whole morning milk for processing.

Subsequently, the milk is poured into copper vats and is heated to 55°C after natural rennet and starter whey are added to facilitate coagulation. The vats consist of an inner copper lining and an outer steel jacket. Steam circulates between the two layers and can be partially recovered by redirecting it back into the steam generator.

Once the curd has sufficiently coagulated, the solid mass is further broken, divided into two parts, and wrapped in linen cloths. These are then placed into molds. These operations are performed mechanically using overhead hoists and monorails. In contrast, the turning and pressing of the cheese wheels over the following three days are carried out manually. During these stages, the production specifications do not impose strict requirements for temperature and humidity, except for maintaining a minimum of 16°C.

At this point, the wheels are ready to be immersed in brine tanks, maintained at 14°C [6], where they remain for a total of 20 days. The wheels are placed in special cages that facilitate their handling.

After this 20-day period, the wheels, which now weigh about 30 kilograms, enter the maturation warehouses, where they must age for a minimum of 12 months at a temperature of at least 16°C and relative humidity of no less than 80%.

The analysis conducted as part of the Erica Project, which took place between 2013 and 2015, indicated that the electrical energy demand of a representative sample of dairy plants ranged from 15 to 93 kWh/t, with an average of 41.4 kWh/t. In terms of thermal energy consumption, values varied between 80 and 140 kWh/t, with an average of 122.7 kWh/t [7]. Consequently, the total average specific energy consumption amounted to approximately 164.1 kWh/t.

3 Energy Demand of Parmigiano Reggiano Production

Accurately quantifying the energy demand associated with Parmigiano Reggiano production is a critical step toward understanding where and how renewable energy sources can be effectively integrated within dairy farms and dairy plants. This analysis provides the foundation for designing tailored energy systems that support sustainability goals while maintaining the efficiency and quality standards of traditional cheese-making operations.

In the dairy industry, energy consumption data for energy audits are typically obtained from utility energy bills. These bills offer aggregated monthly insights into electricity and fuel usage, serving as a readily accessible source of information for energy monitoring. Although not highly detailed, this data can still be instrumental in identifying broader consumption patterns and potential inefficiencies. When analyzed over time, energy bills can help detect anomalies, seasonal fluctuations, or faulty operational behaviors at the macro-level.

Figure 3 presents data derived from the energy bills of a dairy plant over a ten-year period. As shown, natural gas consumption significantly exceeds electricity consumption, accounting for approximately 75% of the plant's total energy use. Seasonal trends are clearly observed for both energy carriers. Natural gas consumption is higher during cold months, with peaks in January and December but also in early spring where milk production is slightly higher. Conversely, electricity consumption tends to rise during the warmer months, with notable peaks in July and August, potentially reflecting cooling and ventilation loads. Year-over-year variability is relatively modest, with standard deviations of natural gas and electricity consumption reaching only 3.8% and 5.0% of the average values over the ten-year period. Total annual energy consumption varies by just 2.1% across the dataset, indicating a high level of consistency and predictability in the plant's energy demand over time.

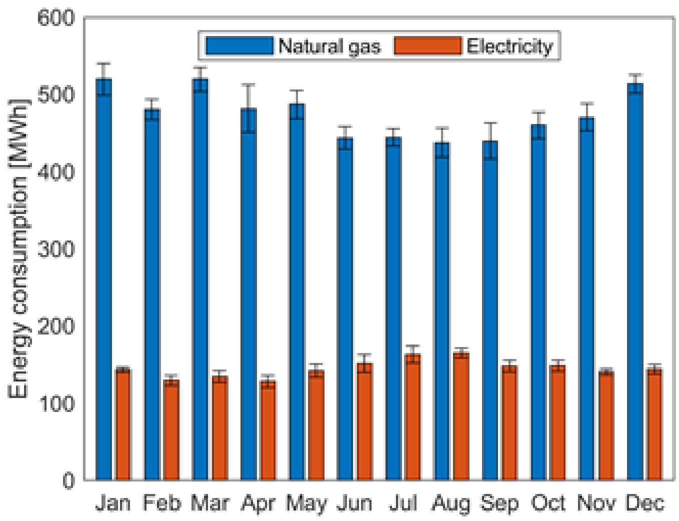

Figure 3. Natural gas and electricity consumption bills

Such consistency in energy consumption over time can largely be attributed to the well-established production patterns typical of specific dairy plants. However, to move beyond the insights gained from a single case study, it is also important to undertake comparative analysis across multiple dairy production sites. This broader approach allows for the identification of sector-wide trends and the establishment of best practices that can enhance energy efficiency and guide renewable energy integration across the industry.

In this regard, Figure 4 shows the monthly energy consumption and corresponding milk processing volumes for three dairy plants across three years. While plants vary significantly in production scale, a strong common correlation between milk quantity and energy consumption can be observed. A regression analysis yields a coefficient of determination R2 equal to 0.92. The Root Mean Square Error (RMSE) is 24.1 MWh, and the Coefficient of Variation of the RMSE (CVRMSE) stands at 0.14, demonstrating good model performance. If compared on an annual basis, the value of R2 rises up to 0.98 and the CVRMSE decreases down to 0.08. These results underscore the robustness of the relationship between production output and energy demand among different dairy plants, reinforcing the potential for benchmarking energy performance at the sectoral level.

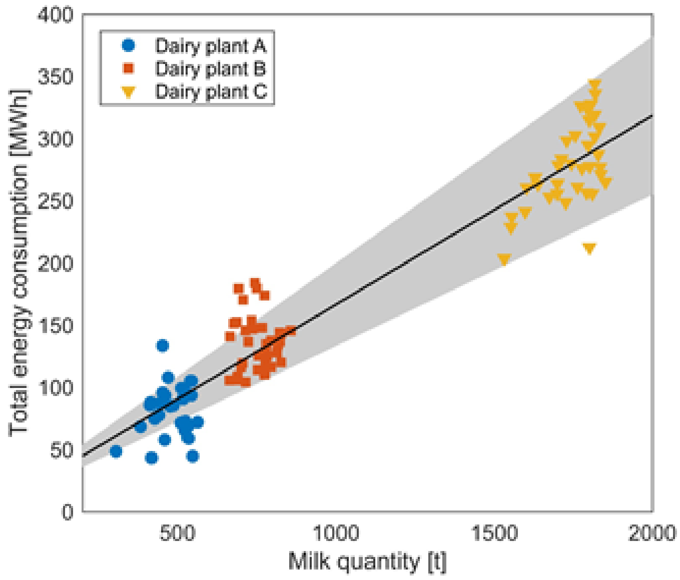

Figure 4. Relation between monthly energy consumption and milk quantity (el + th)

Energy indicators, often referred to as Specific Energy Consumption (SEC), have been developed to promote industrial benchmarking across similar sites [8]. For dairy plants, production can be measured in several ways, including the volume of feedstocks required [9], the mass of products produced [10], or a specific unit that qualifies production in a standardized context, such as a wheel of cheese in the case of Parmigiano Reggiano cheese [2]. For dairy farms, production can be referred to the volumes or mass of milk produced and include protein and fat of energy corrections to ensure comparison between international studies [11]. Relevant scale effects for SEC been demonstrated both for dairy plants [12] and dairy farms [13].

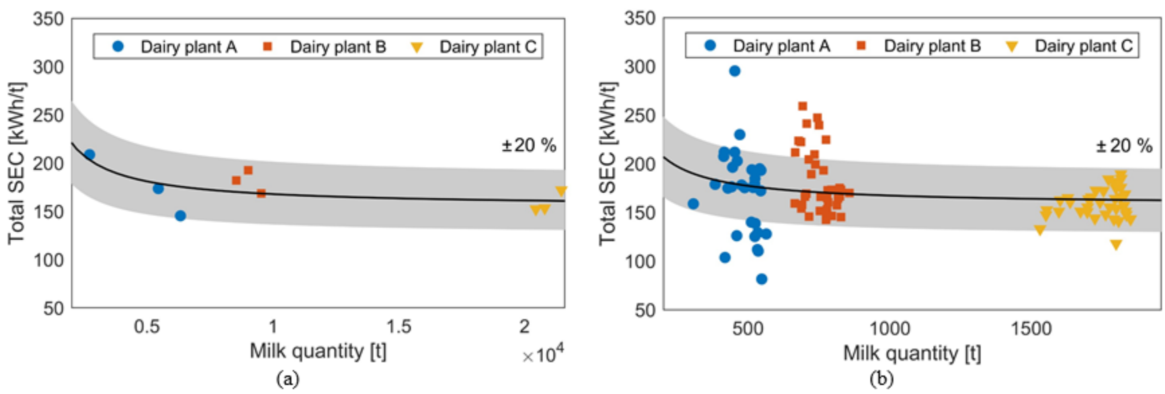

Figure 5. Relation between SEC (el + th) and milk quantity: (a) Yearly values; (b) Monthly values

In this regard, Figure 5 illustrates both the yearly and monthly SEC for the three dairy plants using milk inputs as a measure of production. The annual SEC values for all the three dairy plants fall within a 20% margin of prediction accuracy, confirming the potential for establishing a reliable sectoral benchmark. As shown, monthly SEC values exhibit greater variability, particularly at low production volumes, where fixed or climatic-dependent energy loads have a proportionally larger impact. The electrical and thermal SEC can be expressed as Eqs. (1) and (2), where SECel and SECth are the average yearly electrical and thermal SEC expressed in kWh/t and M is the yearly milk consumption expressed in t/y. Compared to reference [7], this evaluation allows to make scale effects explicit and provide more insights into energy consumption.

$$SEC_{el} = 55.27 + 1.28 \cdot 10^4 / M \tag{1}$$

$$SEC_{th} = 99.61 + 1.18 \cdot 10^5 / M \tag{2}$$

In addition to examining the overall energy consumption of production sites, a crucial aspect for identifying energy efficiency opportunities is the disaggregation of energy use across production processes or plant departments [14]. Depending on the resolution detail, this may require energy monitoring practice that is currently seldom performed in typical dairy plants and farms, especially those with low automation levels. In this context, Table 1 presents the distribution of electricity consumption across various departments in a specific dairy plant equipped with a whey processing section. In this case, the whey processing section accounts for around half of the total electricity consumption, followed by air conditioning and cheese storage with 13.7% and 12.8%, respectively. It is important to note that the proportion of energy end-uses, as well as the performance indicators are strongly influenced by the type of activities that are carried out within each specific production context and therefore require special attention before comparison.

Table 1. Electricity shares by plant departments

Department	Electricity Share
Transformation	8.0%
Treatment plant	6.8%
Storage	12.8%
Services	9.8%
Whey – osmosis	24.4%
Whey – skimming	24.6%
Air conditioning	13.7%

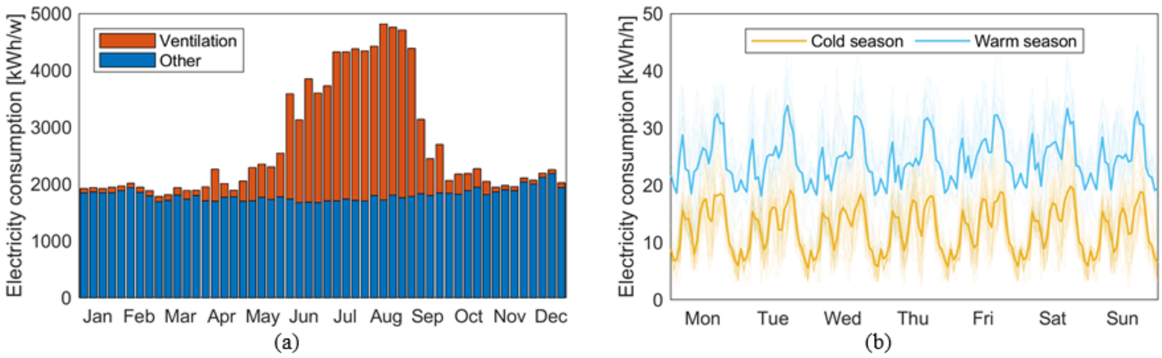

Figure 6. Electricity consumption patterns in a dairy farm: (a) Weekly values; (b) Hourly values

Access to high-resolution energy consumption data is essential for analyzing and reconstructing detailed consumption patterns. Such granular data enables more targeted energy efficiency interventions and the integration of renewable energy sources [12]. Importantly, this level of analysis not only facilitates the interpretation of seasonal consumption trends, but also reveals variations associated with production scheduling as well as calendar-related effects. In current practice, however, this type of information is typically limited for natural gas consumption, while being more readily available for electricity consumption. For instance, Figure 6 shows the weekly and hourly patterns of an electricity meter from a dairy farm, which includes all energy uses except the forage dryer. As shown, ventilation is present only during the warm season, whereas the rest of the electricity consumption remains quite constant throughout the year. Overall, ventilation contributes 24.1% of energy use, causing a 49.6% increase of the hourly peak. From an hourly pattern perspective, the overall weekly load profile can be analyzed by partitioning the dataset into cold and warm seasons. In this case, this is performed by applying a threshold of 30% on the weekly ventilation energy consumption relative to its maximum observed value. In the warm season, the hourly profile exhibits two prominent peaks occurring in the early morning and afternoon, which can be ascribed to the bi-daily milking process [15]. Notably, a third peak in energy demand emerges around midday in the cold season. Throughout the year, no significant differences are observed between working and non-working days as opposed to dairy plants [12], highlighting the consistency of energy use driven by livestock care and milking activities.

4 On-Site Renewable Energy Potential

Increasing the penetration of on-site renewables in dairy plants can be mainly linked to the optimal exploitation of the solar resource and the valorization of waste material into bioenergy.

4.1 Solar Energy

Solar energy is an interesting on-site resource that can be exploited by implementing photovoltaic modules and thermal collectors to meet the electrical and low-temperature thermal energy needs of the dairy industry, respectively. Proper implementation in dairy farms and plants depends on matching energy loads with intermittent energy generation. While solar thermal has a more pronounced seasonal trend and an energy output that can be more easily stored [16], solar photovoltaic requires significant storage capacity to minimize interactions with the grid.

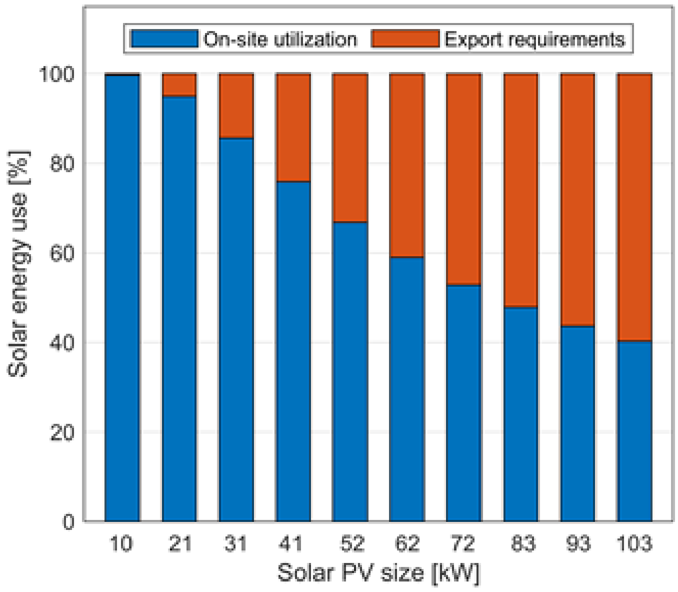

Figure 7. Solar PV integration in a dairy farm

Figure 7 illustrates the on-site utilization and export requirements for the implementation of solar photovoltaics in a dairy farm with a total electricity demand of around 139 MWh. Considering a monthly solar irradiance that peaks at approximately 230 kWh/m^2 in July and reaches a minimum of 36 kWh/m^2 in December, corresponding to a capacity factor of 1346 equivalent hours and a local electricity generation profile [17], on-site utilization and grid sale requirements are evaluated for PV sizes varying from 10% to 100% of the total electricity demand, corresponding to 10 and 103 kW, respectively.

As shown, the self-consumption rate drops dramatically from around 99% to around 40% when the energy demand-supply ratio reaches 1:1. This sharp decline is primarily attributed to the mismatch between generation and demand: a substantial portion of energy consumption occurs during non-daylight hours when PV output is unavailable, causing energy surplus in daylight hours. This outlines the need for energy storage to maximize the self-sufficiency of the dairy industry.

The impact of an ideal electrical storage can be evaluated by assuming that the monthly electricity surplus is utilized within the dairy farm. For the case of a 1:1 ratio between electricity demand and supply, self-consumption increases from 39% to 88%, almost doubling its value. The remaining part that is not used within the farm boundaries is concentrated around April and May, for which solar generation is increasing but ventilation demands are still not significant.

4.2 Bioenergy

To further enhance the sustainability of the Parmigiano Reggiano cheese production process, a well-established approach involves the implementation of a biogas production facility for the generation of both electrical and thermal energy [18]. Biogas, a renewable energy source, is produced through the anaerobic digestion of organic matter. In the context of the present study, cattle manure represents a particularly valuable substrate for biogas generation, though other opportunities in the dairy industry include the valorization of byproducts such as whey and dairy wastewaters. Biogas production typically ranges between 1.51 and 2.17 Nm^3 per animal per day [19], with an average high heating value of 23.4 MJ/Nm^3 [20]. This corresponds to a conservative estimate of 35.3 MJ of chemical energy available per animal per day. Assuming electrical and thermal efficiencies of 22% and 65%, respectively, for a cogeneration system [21], this translates into approximately 2.2 kWh of electrical energy and 6.4 kWh of thermal energy produced per animal per day.

From the dairy farms considered, it is possible to estimate a milk production for each lactating cow of about 35 kg of milk per day, resulting in about 63 Wh of electric energy and 183 Wh of thermal energy per kg of milk produced from the valorization of this byproduct (just considering the contribution of lactating heads). The primary residue from biogas production is the digestate, composed of undigested biomass and microbial content. While it is commonly applied to agricultural fields as a fertilizer, its use may be subject to regulatory or agronomic limitations due to its chemical composition [22].

Subsequently, the potential use of digestate as a fuel in a gasification system is evaluated, aiming to establish a secondary process that enables further exploitation of the energy content of manure. The amount of digestate produced from the anaerobic digestion process is estimated by assuming a biogas yield of 0.3 m^3 per kilogram of dry manure [23]. Considering a biogas density of 1.22 kg/m^3 [23, 24] and applying the principle of mass conservation, the digestate yield is calculated to be approximately 63.4%. This implies that for every kilogram of manure used in biogas production, over 60% remains as digestate, which can potentially be further processed to recover energy through gasification. Considering that a lactating cow excretes an average of 7.3 kg of dry manure per day, approximately 4.6 kg of digestate are generated per animal per day.

Table 2 reports the results of the ultimate and ash analyses conducted on a digestate sample collected from a Parmigiano Reggiano cheese production farm.

Table 2. Digestate ultimate and ash analysis

C [%]	H [%]	S [%]	O [%]	N [%]	Ash [%]
44.66	5.70	0.19	39.59	1.59	8.27

From these analysis, an empirical formula for digestate was assumed as CH1.532O0.6649 as used as an input for biomass gasification model developed by Fock et al. [25] at the DTU.

Assuming a digestate moisture content of 15%, heat losses of 10%, a charcoal yield of 5%, preheating of the gasification air, no steam addition, and a methane content of 2.5% in the product gas, the model predicts a gasification efficiency of 65.6%. This corresponds to 3.447 kWh of chemical energy in the producer gas generated per kilogram of digestate. Assuming the same cogeneration system efficiencies used for biogas (22% electrical and 65% thermal), it is possible to obtain 0.758 kWh of electrical energy and 2.241 kWh of thermal energy per kilogram of digestate. Given an average production of 4.63 kg of digestate per lactating cow per day, this translates into approximately 100 Wh of electrical energy and 296 Wh of thermal energy per kilogram of milk, derived from the thermochemical valorization of digestate. These values are in addition to the energy recovered through anaerobic digestion.

However, two key limitations must be noted. First, commercially available gasification technologies with a level of industrial maturity comparable to anaerobic digestion for processing digestate are currently lacking. Secondly, using digestate in a gasification system implies that it can no longer be applied as fertilizer in the field. A potential alternative, which requires thorough evaluation, is its replacement (either fully or partially) with biochar produced during the gasification process.

4.3 A Quantitative Example

The quantification of the on-site renewable energy potential can be exemplified considering both dairy plants and dairy farms. This requires leveraging the available energy monitoring information regarding the annual energy loads, the identified guidelines for solar PV design, and the quantitative considerations regarding manure valorization.

Table 3. Representative on-site renewable energy potential in a dairy farm with 170 lactating cows

Source	Electrical [kWh/t]	Thermal [kWh/t]
Dairy farm load	64	10
Solar PV – no storage (export)	26 (38)	–
Solar PV – monthly storage (export)	56 (7)	–
Bioenergy – anaerobic digestion	63	183
Bioenergy – gasification	100	296

Table 3 reports the quantitative results for a dairy farm with 170 lactating cows for different strategies of solar and bioenergy exploitation. The electricity and natural gas consumption of the case study amount to 64 kWh/t and 10 kWh/t, respectively. The electricity consumption is in accordance with the value of 73 kWh/t for dairy farms located in Southern Italy, where higher ventilation is required due to extreme temperatures during warm months [13].

The implementation of the PV system alone enables a coverage of 50 kWh/t of electrical energy demand for an energy demand-supply ratio of 1:1, which corresponds to a PV size of 103 kW. The ideal integration of electrical storage highlights an additional 48 kWh/t of on-site utilization, shifting energy generation during day hours to energy use during nighttime.

Regarding bioenergy, the valorization of cow manure can yield 63 kWh/t of electrical energy and 183 kWh/t of thermal energy, entirely meeting the farm's electricity requirements while yielding significant excess of thermal energy. Using digestate as an additional energy resource, on-site potential from bioenergy reaches 163 kWh/t of electrical energy and 479 kWh/t of thermal energy, surpassing both the farm's electrical and thermal energy requirements. Based on Eqs. (1) and (2), corresponding dairy processing operations would require an additional 55 kWh/t (120 MWh) of electricity and 100 kWh/t (216 MWh) of natural gas. With a total energy demand of 119 kWh/t of electricity and 110 kWh/t of thermal energy, bioenergy could completely cover both total electricity and thermal energy requirements, offering an opportunity to allocate surplus energy toward improving animal comfort.

5 Conclusions

This study has investigated the potential for integration of on-site renewable energy into Parmigiano Reggiano production, emphasizing the critical role of proper energy monitoring and deriving guidelines for harnessing solar energy and valorizing dairy waste.

Different levels of energy monitoring were assessed, ranging from aggregated energy bills to the definition of energy performance indicators for their use in benchmarking applications, the disaggregation of energy use among plant departments to identify energy-consuming activities and opportunities for energy efficiency, and the characterization of load profiles for the characterization of energy demand patterns and integration of intermittent renewable energy sources.

Building on these insights, this study has illustrated the quantification of the potential for solar and biomass integration with regard to a dairy farm of 170 lactating cows with annual electricity and natural gas demands of 64 kWh/t and 10 kWh/t. The benchmarking of dairy plants also allowed to identify additional 55 kWh/t of electricity and 100 kWh/t of natural gas for the corresponding dairy processing operations.

For solar energy, direct integration of PV modules enabled coverage of around 4% of the farm's electrical demand, whereas integration of energy storage led to decreasing grid integration requirements to only 12%. On the biomass side, manure valorization via anaerobic digestion yielded potential coverage of 63 kWh/t of electric energy and 183 kWh/t of thermal energy, covering both the farm's electrical and thermal energy requirements. Further digestate gasification would allow to cover milk production and processing electricity requirements, yielding additional thermal energy surplus that could be used to for animal comfort improvement. This demonstrates that the combined use of solar and bioenergy resources can potentially achieve full energy self-sufficiency for dairy installations.

The proposed analysis aims to illustrate the significant potential for renewable energy integration, as a pathway to enhancing the sustainability in food production. Application to a context of national significance such as Parmigiano Reggiano cheese production has highlighted the crucial role of systematic energy monitoring for proper energy management, a practice often underutilized in small and medium-sized enterprises due to technical and socio-economic barriers. The investigation of on-site renewable energy exploitation has led to practical design guidelines, particularly relevant in the context of higher penetration of renewable energy on the national grid, where improved self-sufficiency will become a critical feature of industrial energy systems.

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Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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