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# Potential of Grid-Connected Photovoltaic Systems in Brazilian Dairy Farms

**Antonio José Steidle Neto [1,*], Daniela de Carvalho Lopes [1] and Sheila Tavares Nascimento [2]**

1 Department of Agrarian Sciences, Campus Sete Lagoas, Federal University of São João del-Rei, Rodovia MG 424, km 47, Sete Lagoas, 35701-970 Minas Gerais, Brazil; danielalopes@ufsj.edu.br
2 Department of Animal Science, State University of Maringá, Avenida Colombo, 5790, Maringá, 87020-900 Paraná, Brazil; stnascimento@uem.br
* Correspondence: antonio@ufsj.edu.br

**Abstract:** The insufficient supply of electrical energy, in addition to frequent disturbances and interruptions, has motivated the inclusion of solar, biogas, biomass or wind energy systems in many Brazilian farms. However, there are few studies that have addressed the technical and economic impacts of renewable sources for generating electricity in rural applications, leading farmers not to invest in these technologies for fear of financial losses. This study was carried out to evaluate the potential of grid-connected photovoltaic systems for supplying the electricity demand in dairy farms located at Minas Gerais State, Brazil. The electricity generated by grid-connected photovoltaic systems was estimated from global solar radiation measurements, considering six municipalities of Minas Gerais State, Brazil. Electricity consumption was monitored monthly during one year in 12 farms. The average percentages of electricity consumption in the main operations executed at farms were 4, 27, 12, 33 and 24% for lighting, milking, cleaning/disinfection (water heating and pumping), milk cooling/refrigeration and miscellaneous, respectively. The monthly differences between the electricity generation and consumption for the studied municipalities demonstrated the technical feasibility of grid-connected systems installed directly in the dairy farms, helping to achieve energy sustainability.

**Keywords:** renewable energy; solar radiation models; photovoltaic panels; electricity demand; dairy activities

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## 1. Introduction

In a global context, the milk chain is undergoing a process of accelerated technological modernization in terms of production. Among the world trends, the increase in farm areas, number of cows, volume and quality of milk are highlighted, in addition to the improvement in the genetic potential of the herd [1].

The milk chain in Brazil presents great spatial heterogeneity with respect to herd size, production systems, type of producer and equipment technology. Minas Gerais is the leading milk-producing state in Brazil, having the largest number of dairy farms in the country, as well as many industries and educational and research institutions focused on dairy products.

Energy usage on dairy farms has grown considerably over the past 20 years due to the increase in the number and size of farms as well as the use of automated equipment and 'round-the-clock operation, driven by the increasing demand for dairy products [2]. Nevertheless, in many Brazilian farms, the supply of electricity does not fully meet the demands of dairy activities, presenting frequent disturbances and interruptions. These challenges have motivated the inclusion of solar, biogas, biomass or wind energy systems in the farms. However, there are few studies that have addressed the technical and economic impacts of using these renewable sources for generating electrical energy in rural applications, which leads farmers not to invest in these technologies for fear of financial losses.

The Brazilian energy matrix is mainly based on hydroelectric generation. The low percentage of a supply of renewable sources of electricity directly affects generation stability and price volatility [3], mainly during prolonged droughts. Considering the commercial, residential and industrial classes, the participation of farms in the Brazilian rural areas with decentralized production of electricity must be greatly improved. On the other hand, solar power is found in almost all buildings with decentralized electrical energy systems near the consuming equipment or at the same place [4].

Renewable technologies, such as photovoltaic panels for electricity generation, have traditionally been considered a key mechanism for increasing farm dairy productivity [5]. The expansion of photovoltaic systems for electricity generation is favored by the geographic location of Brazil (mainly the latitude), as well as the microclimate conditions (high solar radiation incidence) [6]. However, this great potential for producing electrical energy must be better exploited in the country. Photovoltaic systems have been successfully used in many applications in Brazil such as residential buildings and electric vehicle charging but have not been extensively studied in the context of dairy farms.

Considering the need for scientific research that encourages the adoption of renewable energy sources in Brazil, this study was carried out to evaluate the potential of grid-connected photovoltaic systems for supplying the electrical energy demand in dairy farms located at Minas Gerais State. The specific objectives were (1) to measure the electrical energy consumption of the dairy activities in different farms and to characterize the electricity usage pattern; (2) to estimate the global solar radiation on tilted panels for determining the electrical energy generated by grid-connected photovoltaic systems in distinct municipalities; (3) to compare electrical energy generation and consumption for demonstrating the potential of photovoltaic systems.

## 2. Materials and Methods

### *2.1. Electrical Energy Demand in Dairy Farms and Meteorological Data*

The monthly electricity consumption of the equipment for milking, lighting (milking parlor, milk tank room and cow buildings), milk cooling/refrigeration and cleaning/disinfection (milking parlor and milk tank room) were monitored during one year in 12 dairy farms situated close to the six selected municipalities of Minas Gerais State, Brazil (Table 1). These cities were chosen taking into account the divisions proposed by the João Pinheiro Foundation [7] as well as the consistency and quality of their meteorological database (2016–2021).

**Table 1.** Geographic coordinates of the selected municipalities of Minas Gerais State, Brazil.

| Region | Municipality | Latitude (°S) | Longitude (°W) | Altitude (m) |
|---|---|---|---|---|
| Jequitinhonha | Águas Vermelhas | 15.75 | 41.46 | 754.07 |
| North | Montes Claros | 16.69 | 43.84 | 645.87 |
| Rio Doce | Caratinga | 19.74 | 42.14 | 609.25 |
| Center | Sete Lagoas | 19.46 | 44.17 | 719.00 |
| South | Varginha | 21.57 | 45.40 | 949.78 |
| Mata | Juiz de Fora | 21.77 | 43.36 | 936.88 |

In this study, similar dairy farms were monitored to ensure a standard during the analyses. The daily operating times of the farm equipment were approximately proportional to 100 lactating cows, and the milking frequencies were two times daily. In addition, all selected farms presented adequate equipment and buildings within the technical requirements for milk production.

An initial data survey showed that the average size of the studied dairy farms (60 ha) is relatively small compared to other countries. However, these farms are growing in terms of milk production volume, averaging from 17 to 26 L cow$^{-1}$ day$^{-1}$. Generally, the sizes of the farms are not directly related to the performance in terms of milk production.

The electricity demand was measured by autonomous data acquisition systems installed in each dairy farm. The consumed energy by each equipment ($E_c$, kWh day$^{-1}$) was calculated based on the power consumption ($P_c$, kW) and the operating frequency (F, h day$^{-1}$):

$$E_c = P_c\, F/1000 \tag{1}$$

The minimum power factor of 0.92 was applied, following the recommendation of the Brazilian Electricity Regulatory Agency (ANEEL) for reducing system losses due to reactive power.

Instead of using sunshine duration data to estimate the global solar radiation on the tilted panels, as was carried out in a previous study [6], measurements of this variable were obtained from the National Institute of Meteorology (INMET) of Brazil. For each municipality, data were measured by pyranometers installed in automatic meteorological stations. Additional analyses were performed on meteorological databases with electronic spreadsheet functions to remove all inconsistent data and missing days.

*2.2. Estimation of the Diffuse and Beam Solar Radiation on Horizontal Panels*

The eccentricity correction factor of the earth's orbit ($E_0$, dimensionless) was determined as [8]:

$$E_0 = 1.000110 + 0.034221 \cos \Gamma + 0.001280 \sin \Gamma + 0.000719 \cos 2\Gamma + 0.000077 \sin 2\Gamma \tag{2}$$

where Γ is the day angle (radians), estimated according to the day number of the year ($d_n$, dimensionless):

$$\Gamma = 2\pi\, (d_n - 1)/365 \tag{3}$$

The declination solar angle (δ, degrees) was calculated based on the formulation [8]:

$$\delta = (0.006918 - 0.399912 \cos \Gamma + 0.070257 \sin \Gamma - 0.006758 \cos 2\Gamma + 0.000907 \sin 2\Gamma - 0.002697 \cos 3\Gamma + 0.00148 \sin 3\Gamma)\, (180/\pi) \tag{4}$$

The sunrise/sunset hour angle ($\omega_s$, degrees) and the diurnal variation of the extraterrestrial radiation on horizontal panels from sunrise to sunset ($H_0$, MJ m$^{-2}$ day$^{-1}$) were determined following the expressions [9]:

$$\omega_s = \cos^{-1} (-\tan \varphi \tan \delta) \tag{5}$$

where φ is the geographic latitude (degrees).

$$H_0 = (24/\pi)\, 4921\, E_0\, [(\pi/180)\, \omega_s\, (\sin \delta \sin \varphi) + (\cos \delta \cos \varphi \sin \omega_s)] \tag{6}$$

On cloudy days, the global solar radiation intercepted by the panels is associated with the cloud cover, acting as an indicator of the diffuse radiation. The clearness index ($K_T$, dimensionless) expresses the ratio between global and extraterrestrial solar radiation, appearing as a tool for characterizing the sky conditions over a particular locality:

$$K_T = H/H_0 \tag{7}$$

where H (MJ m$^{-2}$ day$^{-1}$) is the global solar radiation on horizontal panels, measured by pyranometers. The $H/H_0$ ratio of 0.25 was used whenever Equation (7) resulted in a value smaller than 0.25. This was performed since around 25% of the solar radiation intercepted by the top of atmosphere is incident upon the terrestrial surface mainly as diffuse radiation, even on very cloudy days [10].

Pyrheliometer data from meteorological stations were used [11] to validate the method that correlated $K_T$ with the ratio between diffuse ($H_d$, MJ m$^{-2}$ day$^{-1}$) and global solar radiation on horizontal panels (valid for $0.17 \leq K_T \leq 0.80$) [12]:

$$H_d/H = 1.188 - 2.272\, K_T + 9.473\, K_T^2 - 21.856\, K_T^3 + 14.648\, K_T^4 \tag{8}$$

The beam solar radiation on horizontal panels ($H_b$, MJ $m^{-2}$ $day^{-1}$) was estimated as:

$$H_b = H - H_d \quad (9)$$

*2.3. Estimation of the Global Solar Radiation on Tilted Panels*

Solar panels must be oriented to the North (toward the Equator) in regions located in the Southern Hemisphere. Furthermore, they must be tilted up from the horizontal at an angle that maximizes the global solar radiation interception. The optimal tilt angle (β, degrees) was considered equal to the latitude of each municipality, since the panel inclination will not change throughout the year:

$$\beta = |\varphi| \quad (10)$$

An isotropic model was applied in this study, assuming that the intensity of diffuse sky radiation is uniform over the sky dome and approximating the conditions of an overcast sky. Based on this, the diffuse solar radiation on tilted panels ($H_{d\beta}$, MJ $m^{-2}$ $day^{-1}$) was calculated as [9]:

$$H_{d\beta} = 0.5\ H_d\ (1 + \cos\beta) \quad (11)$$

A conversion factor ($R_b$) was applied when computing the beam solar radiation on tilted panels ($H_{b\beta}$, MJ $m^{-2}$ $day^{-1}$), representing the ratio of the solar radiation incident on the inclined panel to that on a horizontal surface in the absence of the earth's atmosphere:

$$H_{b\beta} = H_b\ R_b \quad (12)$$

For tilted panels installed in the Southern Hemisphere and oriented toward the Equator, the $R_b$ (dimensionless) is obtained as [13]:

$$R_b = \{[\cos(\varphi + \beta)\cos\delta\ \mathrm{sen}\ \omega_s'] + [(\pi/180)\ \omega_s'\sin(\varphi + \beta)\ \mathrm{sen}\ \delta]\}/\{(\cos\varphi\cos\delta\ \mathrm{sen}\ \omega_s) + [(\pi/180)\ \omega_s\sin\varphi\ \mathrm{sen}\ \delta]\} \quad (13)$$

$$\omega_s' = \text{minimum}\ \{\cos^{-1}(-\tan\varphi\tan\delta);\ \cos^{-1}[-\tan(\varphi + \beta)\tan\delta]\} \quad (14)$$

The daily ground-reflected solar radiation on tilted panels ($H_r$, MJ $m^{-2}$ $day^{-1}$) was calculated based on the isotropic reflection [9]:

$$H_r = 0.5\ H\ \rho\ (1 - \cos\beta) \quad (15)$$

where ρ is the albedo (dimensionless), which represented a ground condition covered with vegetation around of the tilted panels and adopted the value of 0.2.

The global solar radiation on tilted panels ($H_\beta$, MJ $m^{-2}$ $day^{-1}$) under isotropic conditions comprised diffuse, beam, and ground-reflected components [14]:

$$H_\beta = H_{d\beta} + H_{b\beta} + H_r \quad (16)$$

*2.4. Grid-Connected Photovoltaic System*

The components of the simulated grid-connected photovoltaic system were a photovoltaic array (multiple solar panels connected together), a power inverter (DC to AC) and a net electricity meter. It was considered that this system was interconnected to the energy cable network of the Minas Gerais State Energy Company (CEMIG). Thus, the surplus electricity generated by the photovoltaic panels and not consumed by the dairy farm was sent to the electricity company power grid, resulting in tax credits to farmers. Contrarily, if the electricity generated by the photovoltaic system was insufficient for supplying the demand, CEMIG provided the required energy. The normative resolution 482/2012 of the Brazilian Electricity Regulatory Agency (ANEEL) established that tax credits can be used for compensating electrical energy consumption (net metering).

In this study, polycrystalline photovoltaic panels were considered due to their lower prices compared to the monocrystalline ones. Furthermore, although this type of panel is usually less efficient than the monocrystalline, it is more eco-friendly to produce. Most of the commercial polycrystalline photovoltaic panels have a 25-year product and performance warranty, guaranteeing at least 90% of the initial power during the first 10 years and 80% during the following 15 years.

An average panel efficiency ($\eta_{pv}$ = 15.87%) and a modular area ($A_{pv}$ = 1.7 $m^2$) were defined based on 25 distinct models of polycrystalline panels, produced by 6 multinational companies. The efficiencies of the polycrystalline panels, provided by the manufacturers, were based on standard test conditions (1000 W $m^{-2}$/25 °C/air mass = 1.5).

In addition to photovoltaic panel efficiency, the electricity generated by the photovoltaic system ($E_{pv}$) also depended on the power inverter efficiency ($\eta_{inv}$) and the efficiency from cable electricity losses ($\eta_{cab}$). The typical efficiency of an inverter for converting direct current into alternating current is 90% [15], while the photovoltaic system cable losses are approximately 2% [16]. Thus, $E_{pv}$ (kWh $day^{-1}$) was estimated from an adapted equation [17]:

$$E_{pv} = [(\eta_{pv}\ \eta_{inv}\ \eta_{cab})\ H_\beta\ (N_{pv}\ A_{pv})]/3.6 \quad (17)$$

where $N_{pv}$ is the number of photovoltaic panels or modules (dimensionless).

The average electrical energy generated by the photovoltaic panels was calculated considering the global solar radiation on tilted panels for each municipality.

## 3. Results and Discussion

Figure 1 presents the average daily profile (24 h) of the dairy activities carried out in the 12 farms located close to the six selected municipalities of Minas Gerais State, Brazil. The time for each milking was approximately 2 h and the time required for cleaning and disinfection (water heating and pumping) of the automatic milking system and the milk tank room was approximately 1 h after each milking. The milk was cooled from 35 °C to 4 °C in about 3 h after the beginning of each milking to avoid the contamination of raw milk by bacteria. This low temperature was maintained during the other day/night hours. Thus, two distinct peaks can be observed in electricity demand every day at regular intervals (from 7 to 10 h and from 17 to 20 h).

The electrical energy usage pattern was subtly variable in the different seasons of the year for specific activities. For example, the lighting time (milking parlor, milk tank room and cow buildings) was minor in summer compared with winter due to the natural photoperiod.

Although it was not a specific objective of this study, early morning and late evening milking start times different from those presented in Figure 1 can reduce farm electricity costs, which is indirectly related with $CO_2$ emissions. This alternative solution can be attractive to the farms since the electricity tariffs during off-peak hours are affordable. This was previously reported in Irish dairy farms [18,19]. However, as in Ireland, Brazilian farmers tend to disagree with changes in milking start times due to the reduced financial benefits, considering the low price paid for the milk in the Brazilian dairy market.

The average percentages of electrical energy consumption in the main operations performed at the monitored dairy farms are shown in Figure 2 The miscellaneous activities (ventilation, misting and manure handling in cow buildings, irrigation water pumping to the pasture and cow brushing) indirectly associated to the milking process were counted together.

The latitudes of the municipalities close to the monitored dairy farms allow natural lighting to be better available than in other countries, where lower photoperiods are common during several months of the year. Additionally, the tropical climate allows the dairy facilities to be built with large windows (milking parlor and milk tank room) or containment fences (cow buildings) instead of lateral closures, enabling solar radiation to illuminate the interior of the installations, generally oriented on the East–West axis. Even so, the average electricity consumption for lighting in Brazilian dairy farms was similar to that in Ireland (4%) [20], probably due to the use of incandescent and fluorescent lamps in many dairy farms of Minas Gerais State, which leads to low energy efficiency. However, in the last years, this type of lamps is gradually being replaced by LED technology.

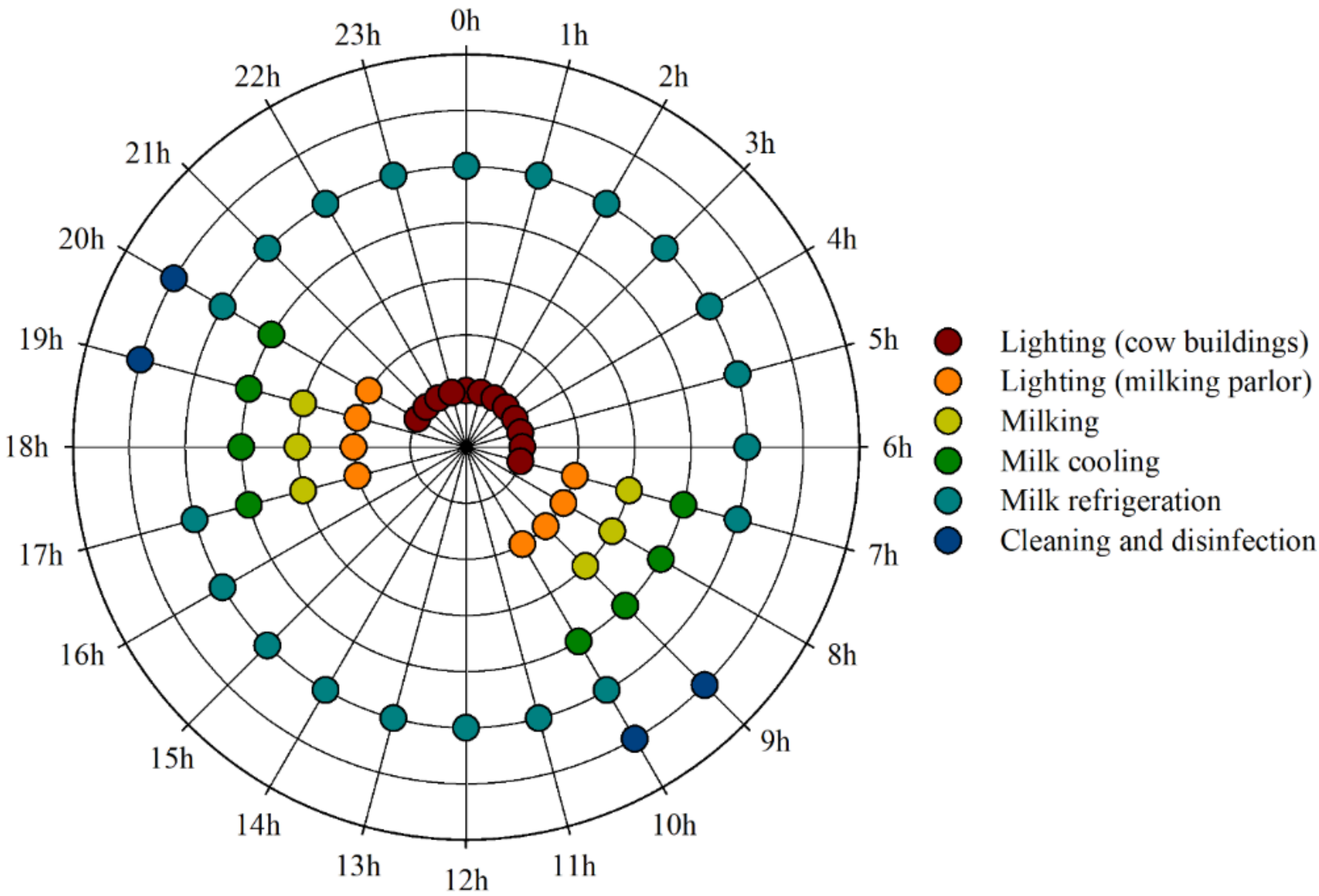


**Figure 1.** Average daily profile of the dairy activities in Brazilian farms.

The average electricity consumption for milking in Brazilian dairy farms (Figure 2) was higher compared to that obtained by other studies [20,21], which reached 20% and 19%, respectively. The prevailing use of milking systems from low to medium energy efficiencies partly explains this result. Few dairy farms in Minas Gerais State are equipped with automatic milking systems of high energy efficiency due to the low price paid for the milk in the Brazilian market [6].

The Minas Gerais State is distinguished by high air temperatures (maximum annual values from 27 to 31 °C on average), making the milk cooling and refrigeration the activity with the largest operating time (Figure 1) and electrical energy consumption (Figure 2). This trend was also reported by previous studies [20–22].

The average electrical energy consumption obtained in this study (Figure 2) was slightly different than the results reported in a previous work, also carried out in Minas Gerais State [6]. The differences were −1%, −6%, −3% and +9% for milking, milk cooling and refrigeration, cleaning and disinfection and miscellaneous, respectively. These variations can be explained by the previous study considering the average electrical energy consumption for dairy farms with distinct herd sizes (66, 106 and 158 lactating cows). Considerable differences can be observed in electricity demands even in dairy farms with similar operations, mainly due to the equipment used in the milking parlor, milk tank room and cow buildings.

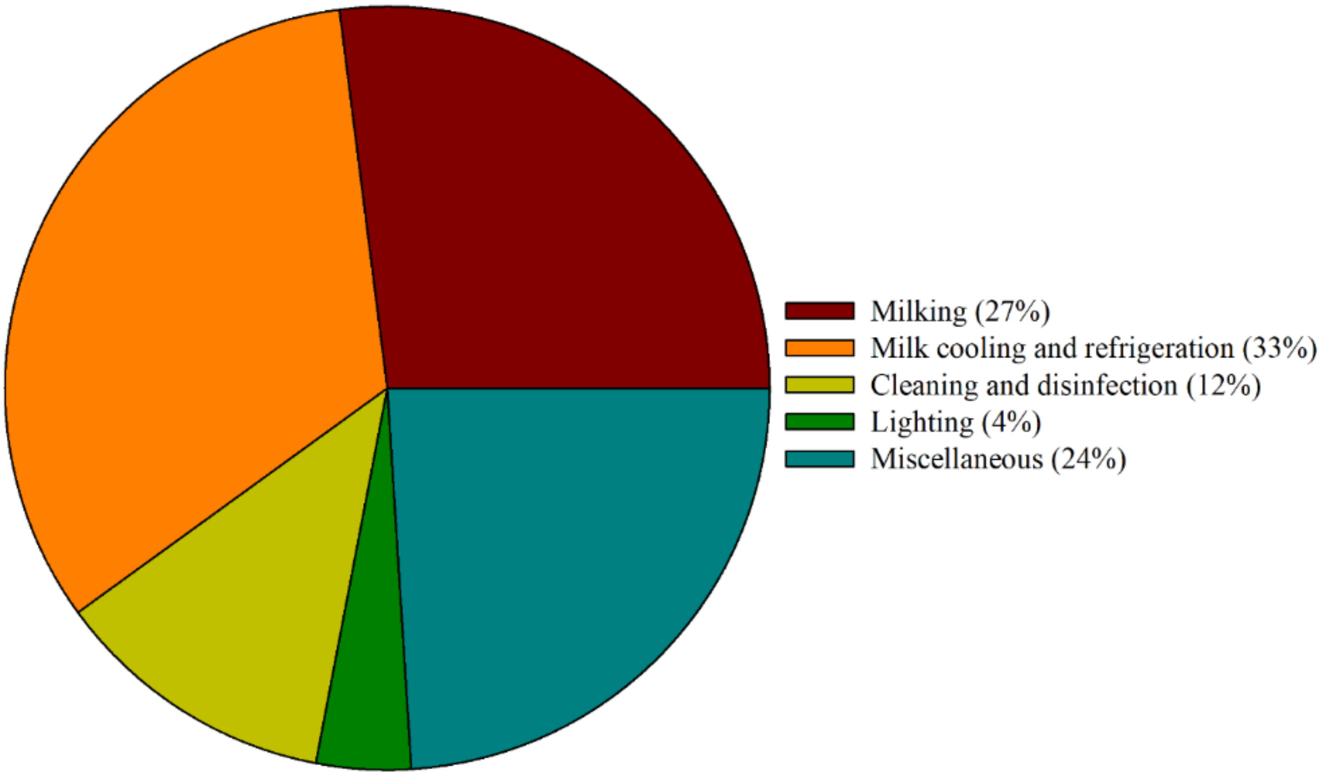


**Figure 2.** Average electrical energy consumption in Brazilian dairy farm operations.

The monthly variations of the difference between the electricity produced by the simulated photovoltaic systems and the measured electrical energy consumption of dairy farms (ΔE) located at the municipalities of Minas Gerais State, Brazil, are presented in Figure 3. Aiming at comparing the studied municipalities, electrical energy generation was estimated taking into account 100 polycrystalline photovoltaic panels (modules), leading to a total area of 170 $m^2$.

Among the municipalities selected in this study, only Águas Vermelhas and Montes Claros presented electrical energy generation higher than the consumption throughout the year by using 100 photovoltaic panel modules. For these municipalities, in addition to meeting the energy demand of the dairy farms, the energy surplus generation presented potential for an accumulation of tax credits by the farmers with the Minas Gerais State Energy Company (CEMIG), which can be used in future requirements. For all the other municipalities, the electrical energy consumption was higher than the generation in the late autumn and early winter (May and June) in the Southern Hemisphere (Figure 3). Additionally, the monthly deficits of electrical energy generation remained throughout the winter and early spring (July, August and September) for the municipalities of Caratinga, Varginha and mainly Juiz de Fora, reaching maximum values of −238 kWh and −388 kWh in Caratinga and Varginha during May, as well as −608 kWh in Juiz de Fora during September.

For all studied municipalities, the months of December, January, February and March promoted the largest positive values of ΔE, coinciding with summer in the Southern Hemisphere. Although the electrical energy consumption of the dairy farms was higher in these months due to the elevated air temperatures combined with the milking, cooling and refrigeration requirements, the maximum energy surplus values varied from 887 kWh in Juiz de Fora to 1825 kWh in Águas Vermelhas, taking into account the month with the highest generation (January).

The higher negative results of ΔE can be mainly explained by the geographical location (latitude) of Varginha and Juiz de Fora, which are located further south of the Minas Gerais State. Additionally, the availability of solar radiation during the winter in all municipalities is typically reduced due to the smaller day lengths.

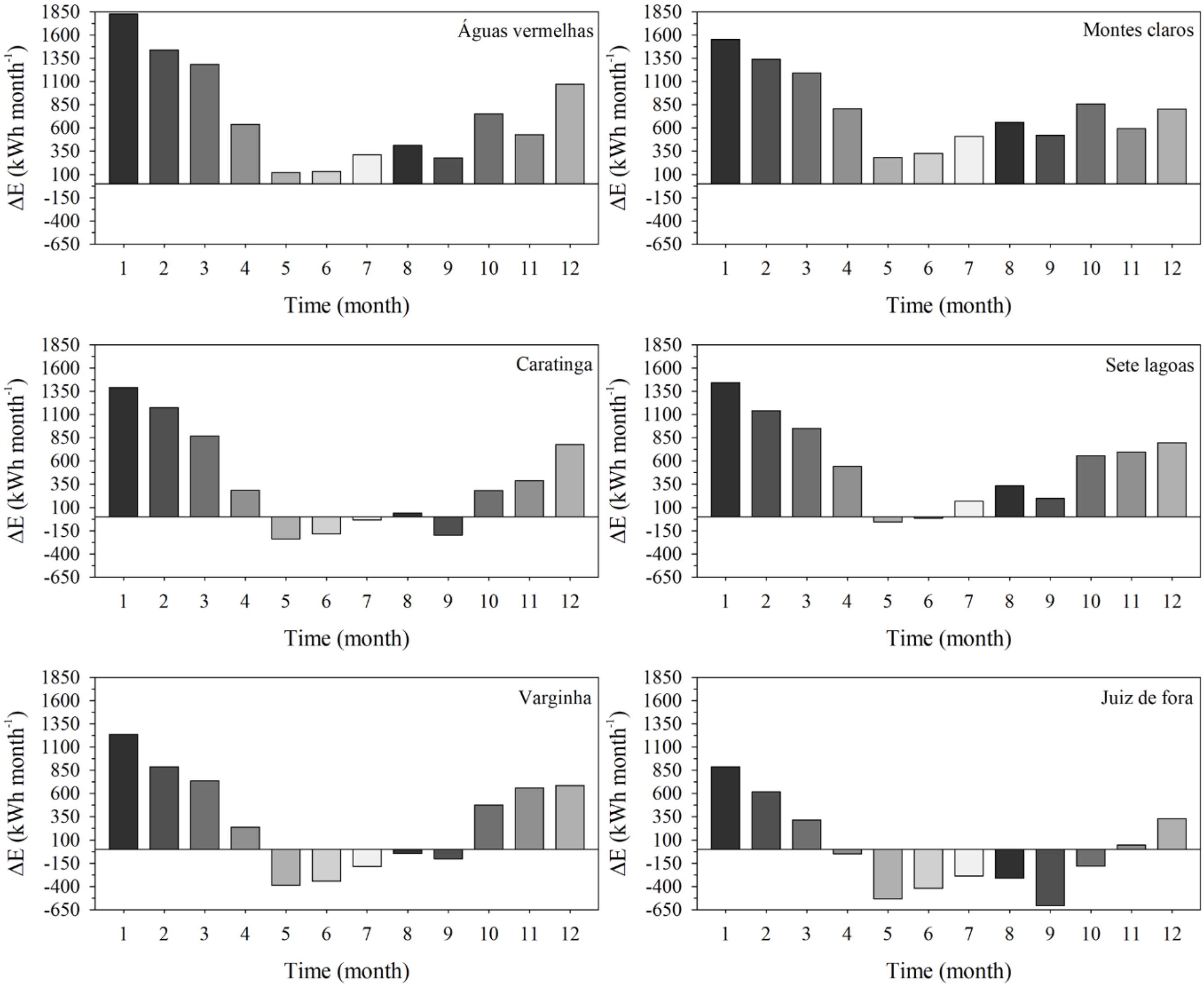


**Figure 3.** Monthly variations of the difference between the electrical energy generation and the electricity consumption (ΔE) for municipalities of Minas Gerais State, Brazil.

Based on the results, it is possible to affirm that the municipalities of Montes Claros and Águas Vermelhas tend to require smaller photovoltaic panel areas to fully meet the energy demands of the dairy farms. Contrarily, Juiz de Fora tends to need the largest photovoltaic panel area and, consequently, the highest initial investment for installing the grid-connected system, as well as greater maintenance costs.

The negative differences of ΔE (Figure 3) can be minimized by increasing the number of photovoltaic panel modules, with the purpose of expanding energy generation. Another possibility is to use the tax credits resulting from the electrical energy generated during the initial and final months of the year that was not immediately consumed by the dairy farm and was sent to the electricity company power grid. In practice, the last purpose will be fully effective from a financial standpoint if the tax credits are sufficient to supply the energy consumption charges resultant from the external energy network. Furthermore, based on these considerations, it is possible to affirm that the number of photovoltaic panel modules in Águas Vermelhas and Montes Claros must be optimized, aiming at reducing the discrepancies between the monthly electrical energy generations and demands. This optimization requires a complex economic analysis, considering the tax credits received by the dairy farm for each kWh injected in the external network, and the values paid for each kWh consumed by the dairy farm from the external network. Other data are the differentiated tariffs charged by CEMIG depending on the month and daytime, as well as the initial investment and maintenance costs required by the photovoltaic system. Since the highest percentage of the Brazilian energetic matrix is concentrated on hydroelectric sources, monthly tariffs charged by CEMIG are generally changed according to the water level in the reservoirs upstream of the turbines that generate electricity.

However, it is important to highlight that the months with electricity production equal or greater than the consumption do not imply independent photovoltaic systems in terms of meeting the electrical energy demand. Power consumption peaks are possible depending on the operation of dairy farm equipment, and many times do not coincide with periods of higher electricity generation. On the other hand, the grid-connected photovoltaic systems allow consumption peaks to be supplied by the energy company grid. Regardless of this limitation, the external demand is compensated in other periods when the surplus electricity generated by the photovoltaic panels is sent to the electricity company power grid. The normative resolution 482/2012 of the ANEEL further establishes that Brazilian farmers must pay a monthly tariff, called electricity availability cost, which includes federal and state taxes, and is independent of the requirements of energy consumption from the external network.

One possible way to avoid this situation is to install a stand-alone photovoltaic system, which is independent of the utility grid. This system requires higher initial investment and maintenance costs due to the battery pack and charge controller that also compose its structure.

Commercial polycrystalline photovoltaic panels with a lifetime of 25 years and 15.87% average efficiency were considered in this study. However, there are experimental solar panels with different designs and purposes, which can improve the photovoltaic system performance and increase its lifetime. A hybrid photovoltaic and thermal solar energy collector with integrated phase change material was proposed [23], enhancing the daily electrical efficiency by 7.43% compared to the traditional solar module. The lifetime of solar panels with a polysiloxane compound can be increased from 20–25 to 40–50 years, while the efficiency of photoelectric conversion of solar radiation can be improved up to 28% [24]. Additionally, solar roof panels, manufactured with laminating and encapsulating technologies with a two-component polysiloxane compound [25], are interesting options for dairy farms, as they perform power-generating, heat-generating (warm water for dairy processes) and construction functions (protect cow buildings).

The methodology and equations used in this research are suitable for dairy farms in other countries and geographic areas. The $\Delta E$ variability will depend mainly on the latitude, meteorological conditions, and consumption of electrical energy. The technology of the equipment associated with dairy activities and the photovoltaic system will also contribute to this variability.

## 4. Directions for Further Research

Future studies will include the validation of the estimates presented in this research through in situ measurements of the electrical energy generated by photovoltaic panels physically installed in some of the evaluated dairy farms. Additionally, measurements of the electricity generated by the photovoltaic systems can be carried out at tilt angles different from the local latitude with the purpose of analyzing the capacity of electrical energy production in distinct seasons. The proposed methodology can also be applied to different rural buildings, such as poultry and swine farms.

## 5. Conclusions

The percentages of electrical energy usage associated to dairy activities were similar to previous studies. Unfortunately, due to the low price paid for milk in the Brazilian dairy market, the investment in more efficient equipment (with low electrical energy consumption) is still reduced. This is one of the reasons for the high average electrical energy consumption obtained in this study, mainly for milking and lightning.

Although the latitude values among the studied municipalities presented a maximum difference of 6°, this geographic coordinate and global solar radiation were the most relevant variables when simulating the generated electrical energy by the photovoltaic panels.

The monthly variations of the difference between the electrical energy generation and consumption for the studied municipalities of Minas Gerais State demonstrated the technical potential of grid-connected systems installed directly in Brazilian dairy farms. However, future studies are required for optimizing the number of photovoltaic panel modules for each municipality based on economic analyses. The methodology proposed in this study is further suitable for dairy farms in other countries and geographic areas, as well as for different rural buildings, such as poultry and swine farms.

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## Abbreviations

| | |
|---|---|
| $A_{pv}$ | Modular area of the photovoltaic panel ($m^2$) |
| $d_n$ | Day number of the year (dimensionless) |
| $E_0$ | Eccentricity correction factor of the earth's orbit (dimensionless) |
| $E_c$ | Consumed energy by the equipment (kWh $day^{-1}$) |
| $E_{pv}$ | Electrical energy generated by the photovoltaic system (kWh $day^{-1}$) |
| F | Operating frequency of the equipment (h $day^{-1}$) |
| H | Global solar radiation on horizontal panels (MJ $m^{-2}$ $day^{-1}$) |
| $H_0$ | Extraterrestrial solar radiation on horizontal panels (MJ $m^{-2}$ $day^{-1}$) |
| $H_b$ | Beam solar radiation on horizontal panels (MJ $m^{-2}$ $day^{-1}$) |
| $H_{b\beta}$ | Beam solar radiation on tilted panels (MJ $m^{-2}$ $day^{-1}$) |
| $H_d$ | Diffuse solar radiation on horizontal panels (MJ $m^{-2}$ $day^{-1}$) |
| $H_{d\beta}$ | Diffuse solar radiation on tilted panels (MJ $m^{-2}$ $day^{-1}$) |
| $H_r$ | Ground-reflected solar radiation on tilted panels (MJ $m^{-2}$ $day^{-1}$) |
| $H_\beta$ | Global solar radiation on tilted panels (MJ $m^{-2}$ $day^{-1}$) |
| $K_T$ | Clearness index (dimensionless) |
| $N_{pv}$ | Number of photovoltaic panels or modules (dimensionless) |
| $P_c$ | Power consumption of the equipment (kW) |

$R_b$ Conversion factor (dimensionless)
$\beta$ Optimal tilt angle (degrees)
$\delta$ Declination solar angle (degrees)
$\eta_{cab}$ Efficiency from cable electricity losses (%)
$\eta_{inv}$ Inverter DC to AC efficiency (%)
$\eta_{pv}$ Photovoltaic panel efficiency (%)
$\rho$ Ground albedo (dimensionless)
$\varphi$ Geographic latitude (degrees)
$\omega_s{}'$ Minimum value of sunrise/sunset hour angle (degrees)
$\omega_s$ Sunrise/sunset hour angle (degrees)
$\Gamma$ Day angle (radians)

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