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*Journal of Energy and Power Technology*

Research Article

# Grid-Connected Photovoltaic System for Generating Energy to Dairy Farm Activities

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**Academic Editor:** Mohammad Jafari

**Collection:** Optimal Energy Management and Control of Renewable Energy Systems

*Journal of Energy and Power Technology*
2024, volume 6, issue 3
doi:10.21926/jept.2403016

**Received:** April 28, 2024
**Accepted:** August 18, 2024
**Published:** August 26, 2024

**Abstract**

Minas Gerais is the leading milk-producing state in Brazil, and many dairy activities are supplied with electricity by the cable aerial network of the electrical energy state company. Given that the Brazilian energy matrix relies primarily on hydroelectric power, studies on the potential of other renewable energy sources in the context of dairy farms are innovative. Additionally, frequent disturbances and interruptions have motivated the installation of solar energy systems on dairy farms. However, the scarcity of technical and scientific studies demonstrating the benefits of electricity generated from photovoltaic panels in Minas Gerais has caused dairy farmers to fear potential financial losses. In this study, grid-connected photovoltaic systems in dairy farms were evaluated, considering three fixed tilt angles for the panels (latitude - 10°, latitude, and latitude + 10°) and electrical energy demands of dairy activities associated with two herd sizes (100 and 150 cows). Meteorological databases and mathematical models were used to predict daily global radiation on tilted panels in dairy farms of two Brazilian municipalities of Minas Gerais State (Lavras and Paracatu). Energy consumption related to dairy activities was monitored for 12 months. For both municipalities, the best results were verified with the tilt angle of panels equal to the local latitude - 10°. The municipality with the lowest latitude (Paracatu) showed higher electricity generation potential. In all simulated scenarios, a greater energy surplus was found from late spring to early autumn (Southern Hemisphere), when the higher electricity generation by the photovoltaic panels met the elevated electrical energy demand of the dairy farms. A high energy surplus was also verified during midwinter, where lower energy consumption by the dairy farms compensated for the reduced availability of solar radiation. The proposed methodology can be adapted to other dairy farms, agricultural and urban buildings.

**Keywords**
Photovoltaic panels; tilt angle; solar radiation models; dairy farms; agricultural buildings

## 1. Introduction

Energy generation by photovoltaic systems is growing worldwide, with the main objective of meeting electricity demand sustainably and distributedly [1]. Among the different types of photovoltaic systems, grid-connected and building-integrated systems prevail in rural and urban areas, providing the energy needs for various applications. At the same time, the surplus electricity is injected into the grid [2, 3].

Brazil has implemented several incentive programs for sustainable energy. These include a public call from the Brazilian Electricity Regulatory Agency (ANEEL) aiming to create experimental photovoltaic power plants connected to the national electricity system [4]. Other initiatives were the Normative Resolutions 481/2012, 482/2012, and 687/2015, also published by ANEEL, that regulate the distributed photovoltaic energy generation in Brazil [5, 6]. Photovoltaic systems for electrical energy generation in Brazil are favored by the high incidence of solar radiation due to the country's geographic location. Despite the advances and availability of solar resources, photovoltaic participation in electricity generation remains incipient, representing only 2.6% of the Brazilian energy matrix [7].

Dairy farms are relevant consumers of electricity, with greater potential for integrating renewable energy resources [8]. Among the main infrastructure problems faced by the Brazilian dairy farms are oscillations, frequent disturbances, and interruptions in the supply of electricity by the cable aerial network of the energy state company. Furthermore, the electricity supplied by the energy company is frequently exposed to rising costs, motivating the adoption of renewable and independent energy sources installed directly in the farms [9].

Scientific research about more sustainable electrical energy generation and demand flexibility initiatives in the dairy sector is increasing. Hybrid photovoltaic-thermal collectors were successfully used to simultaneously provide energy and heat to a large dairy farm in Southern Italy [2]. Altering the practices or employing energy storage technologies in large-scale New Zealand dairy farms showed potential for providing a cost-effective approach to balance electricity grids [8]. A long-term evaluation of energy generation from photovoltaic panels in dairy farms with different fixed tilt angles was performed for the Brazilian municipalities of Pedra Azul, Sete Lagoas, and Juiz de Fora, indicating greater seasonal differences in electricity generation as latitudes increase [10]. Using milking start times from 06:00 to 20:00 h in Irish dairy farms maximized the net profit and minimized electricity-related $CO_2$ emissions [11]. Also, in Irish dairy farms, collecting per-cow information regularly to support herd monitoring and decision-making tended to enhance economic sustainability by increasing dairy gross margin and milk yield [12].

Brazilian milk production is very heterogeneous in relation to the farm locations, herd sizes, type of producer, cattle, and production systems. Producers investing in technology to obtain higher-quality milk are concentrated mainly in the Brazilian States of Minas Gerais, Paraná, São Paulo, and Goiás [13]. According to [14], Minas Gerais State is the major producer of milk in Brazil, reaching the amount of 6.2 billion liters in 2021 and comprising approximately 25% of the total production in the country. Minas Gerais has the largest number of licensed industries in the dairy sector, with more than 300 licenses, corresponding to an average production of 100,000 L of milk per day.

Considering that the Brazilian energy matrix is predominantly hydroelectric, more scientific research is needed to demonstrate the benefits and the potential of other renewable energy sources. Many Brazilian farmers do not invest in photovoltaic systems due to the lack of technical and scientific knowledge, but also for fear of financial losses. In this context, grid-connected photovoltaic systems in dairy farms were evaluated for different fixed tilt angles of panels, herd sizes, and geographic coordinates at Minas Gerais State, comparing the electrical energy generation and consumption.

## 2. Material and Methods

### *2.1 Estimation of Electrical Energy Generation by Photovoltaic System*

Long-term databases (greater than 33 years) of the sunshine duration for two Brazilian municipalities of the Minas Gerais State (Lavras and Paracatu) were provided by the National Institute of Meteorology (INMET). These municipalities were chosen taking into account the consistency and quality of meteorological data, the expressive production of raw milk from dairy farms, and the number of establishments of milk processing registered in the database from the Federal Inspection Service of Brazil. For each municipality and day of the year, the arithmetic average of sunshine durations was calculated considering all the years of the databases.

The meteorological variable related to the length of time during which direct solar radiation is above 120 W $m^{-2}$ (sunshine duration) was measured by Campbell-Stokes recorders (Negretti & Zambra, London, UK). This instrumentation is installed at conventional meteorological stations of the INMET, located in each municipality studied.

The inconsistent data and missing days were excluded from the databases using electronic spreadsheet functions. In addition, comparisons with day length data were performed, considering that the sunshine duration may have a maximum value equal to the length of a sunny day. Visual analysis of graphs was also used as a complementary tool.

Sunshine duration measurements, day number of the year, geographic latitude, and tilt angle of photovoltaic panels (Table 1) were used in isotropic models for estimating, on a daily scale, all variables necessary for calculating the global solar radiation on tilted panels. The isotropic models consider that the energy of diffuse radiation is uniform over the sky dome. All mathematical models were implemented in electronic spreadsheets.

**Table 1** Geographic coordinates and tilt angles of photovoltaic panels evaluated in this study.

| Municipality* | Latitude (ϕ) (° S) | Longitude (°W) | Tilt angle of panels (°) | | |
|---|---|---|---|---|---|
| | | | \|ϕ\| - 10° | \|ϕ\| | \|ϕ\| + 10° |
| Paracatu | 17.24 | 46.88 | 7.24 | 17.24 | 27.24 |
| Lavras | 21.75 | 45.00 | 11.75 | 21.75 | 31.75 |

*Minas Gerais State, Brazil.

A flowchart was developed to improve the understanding of the sequence and interactions among all variables required for calculating global solar radiation (Figure 1). The mathematical models used for estimating global solar radiation on tilted panels were proposed and/or indicated by renowned and recognized researchers in the field of solar radiation (Yadav, A.K. and Chandel, S.S. [15]; Iqbal, M. [16]; Collares-Pereira, M. and Rabl, A. [17]; Spencer, J.W. [18]; Liu, B.Y.H. and Jordan, R.C. [19]; Prescott, J.A. [20]). The models were chosen due to their scientific relevance but mainly because of the accuracy of their predictions compared to actual measurements.

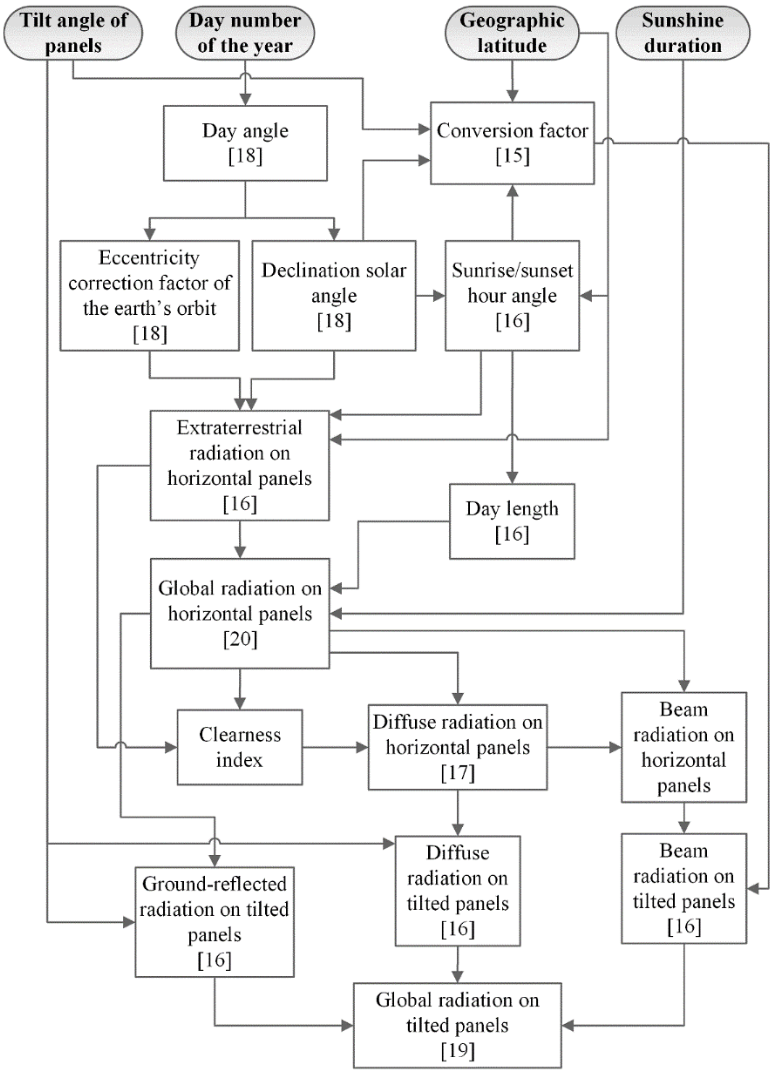


**Figure 1** Variables and associated references required for predicting the global solar radiation on tilted photovoltaic panels.

High global solar radiation is one of the variables that affect photovoltaic system performance. However, the system's optimum performance depends on the amount of global solar radiation incident on the solar panels, which is directly associated with the tilt angle of the panels. Most previous scientific studies recommended setting the tilt angle of the panels to a value equal to or very close to the latitude of the local [21], especially for annual tilt angles [22]. Also, there are several other propositions, such as the one suggested by [23], which calculated the optimum tilt angle as the latitude + 10° to maximize the global solar radiation incident on the panels installed in South Africa. On the other hand, [24] indicated the annual optimum tilt angle as latitude - 10° in England. As there are no previous studies for the municipalities evaluated (Lavras and Paracatu), the tilt angles were defined exclusively based on adjusting the panels to the local latitude, allowing a variation of ±10° around this value. This range was pre-established to evaluate the positive and negative impacts of slight differences from the local latitude value, considering that the fixed photovoltaic panels are often installed with a tilt angle equal to the roof pitch of the agricultural buildings.

In this study, the estimations of the global solar radiation on tilted panels followed the technical recommendation that the panels must be oriented towards the true north in the Southern Hemisphere. Also, it was assumed that on very cloudy days, at least 25% of the global solar radiation intercepted by the top of the atmosphere reaches the Earth's surface, especially as diffuse radiation [25]. The ground-reflected radiation on tilted photovoltaic panels was also estimated considering an isotropic reflection [16].

The grid-connected photovoltaic system (modular panel set, inverter DC to AC, and electricity meter) was adopted in this study due to its lower complexity and cost-effectiveness compared to the off-grid systems. This photovoltaic system is interconnected to the electrical energy company's transmission and distribution cable aerial network. The electricity generated and not consumed in dairy farm activities is fed into the energy company's power grid, resulting in tax credits for farmers. On the other hand, if the energy generated from the photovoltaic panels is insufficient for consumption, the company's cable network provides the required electricity. According to the normative resolution 482/2012 of the ANEEL, Brazilian farmers using grid-connected photovoltaic systems must pay a monthly fee called electricity availability cost. This fee includes state and federal taxes, regardless of whether the farmers consume energy from the external network. Energetic independence is possible with a stand-alone photovoltaic system (off-grid), which requires a higher initial investment, mainly due to additional components, such as battery pack and charge controller.

Based on the average physical and technical features of 25 models of polycrystalline panels manufactured by 6 international companies, 100 photovoltaic panels were considered in this study, each one with a 1.7 $m^2$ modular unit area, 60 cells with individual dimensions of 156 × 156 mm, 275 W of rated maximum power, and 16.8% of average efficiency, obtained under standard test conditions of 25°C, 1.5 air mass, and 1000 W $m^{-2}$. High-efficiency photovoltaic panels (19-21%) require the use of high-quality materials with minimal impurities and manufacturing processes that reduce defects. Based on the Brazil's high custom tariffs and the devaluation of the Brazilian currency compared to the US dollar and the euro, polycrystalline panel models with slightly lower efficiency were considered in this study to improve the cost-benefit ratio.

According to [26], the typical efficiency of an inverter DC to AC is 90%, and the average energy losses in the photovoltaic system cables are around 2%. The electrical energy generated by the photovoltaic system ($E_{pv}$), in kWh $day^{-1}$, was estimated using Equation (1), considering the global solar radiation on tilted panels ($H_\beta$), in MJ m$^{-2}$ day$^{-1}$, the number of photovoltaic panels or modules ($N_{pv}$), dimensionless, the modular unit area of the panel ($A_{pv}$), in m$^2$, and the system efficiencies ($\eta_{sys}$):

$$E_{pv} = \left[H_\beta \eta_{sys}\left(N_{pv}A_{pv}\right)\right]/3.6 \quad (1)$$

### *2.2 Measurement of Electrical Energy Consumption in Dairy Farm Activities*

Dairy farms with similar characteristics related to the number of lactating cows and milk production infrastructure were selected for this study. Thus, according to the Brazilian patterns, farms were divided into medium (100 cows) and large (150 cows) scales. These herd sizes were considered as scenarios during the analyses.

The electrical energy variables (voltage (V), current (A), active power (W), active energy (Wh), apparent power (VA), and power factor) associated with dairy activities (lighting, milking, milk cooling/refrigeration, cleaning/disinfection, and miscellaneous) were measured daily by autonomous data acquisition systems (model UX120-018, Hobo Plug Load Data Logger, Onset, USA) during 12 months at dairy farms located near the municipalities studied.

The electricity consumed by each equipment installed in dairy farms was calculated based on power consumption and operating frequency. On-farm energy consumption was directly related to livestock building, milk production, herd size, and climatic conditions.

## 3. Results and Discussion

The monthly variations in global solar radiation intercepted by the photovoltaic panels, considering the three tilt angles (latitude - 10°, latitude, and latitude + 10°), are shown in Figure 2 and Figure 3 for Lavras and Paracatu municipalities, respectively, including the variability of average air temperature.

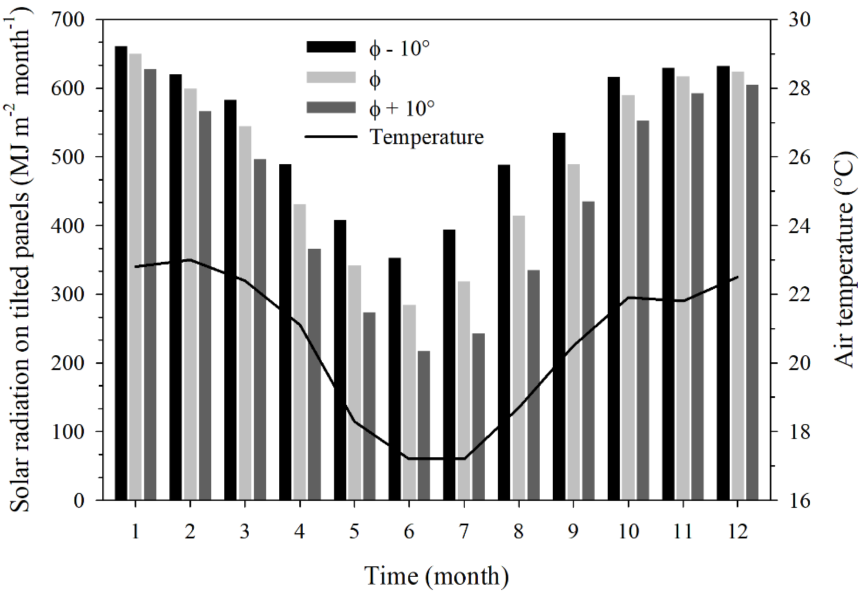


**Figure 2** Monthly variations in air temperature and global solar radiation for the different tilt angles of photovoltaic panels in the municipality of Lavras (21.75° S), Minas Gerais State, Brazil.

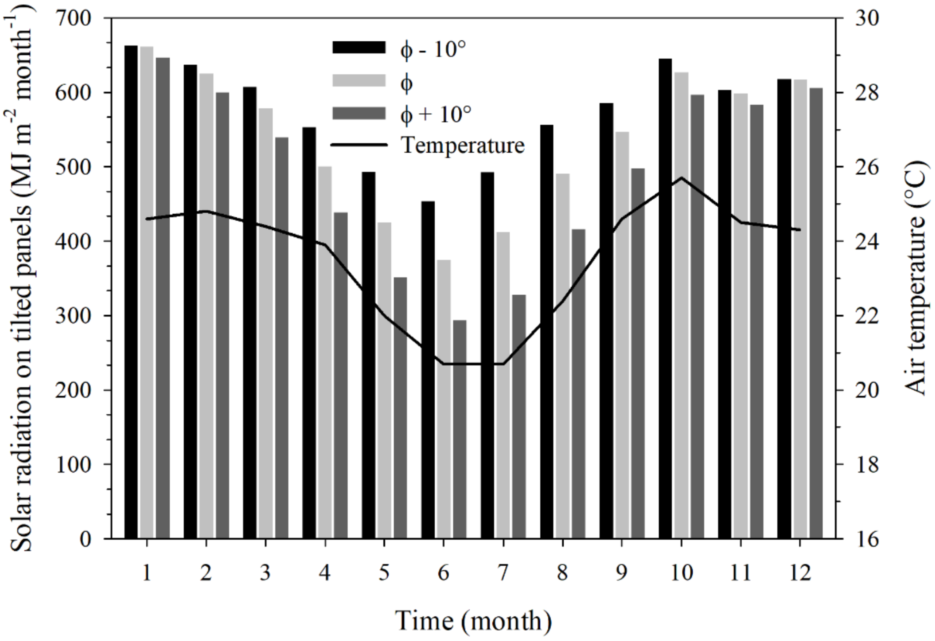


**Figure 3** Monthly variations in air temperature and global solar radiation for the different tilt angles of photovoltaic panels in the municipality of Paracatu (17.24° S), Minas Gerais State, Brazil.

The differences between the monthly global solar radiation values intercepted by the photovoltaic panels in Figure 2 and Figure 3 are associated mainly with the geographical position (latitude coordinate) of the municipalities of Lavras and Paracatu. Thus, during the year, higher global solar radiation values were verified in Paracatu than in Lavras. In terms of tilt angles of the panels, a consistent trend was observed across both municipalities considering the monthly global solar radiation, with higher values at the latitude - 10°, intermediate values at the latitude, and lower values at the latitude + 10°. However, during the months with higher air temperatures (first and last quarter of the year), the differences in global solar radiation between the three tilt angles for the same month and municipality were less pronounced compared to the months with lower air temperatures (winter season).

The monthly electricity consumption for the main activities (lighting, milking, milk cooling/refrigeration, cleaning/disinfection, and miscellaneous) performed at the monitored dairy farms are presented in Table 2 for distinct herd sizes (100 and 150 cows). The miscellaneous activities (ventilation, misting, manure handling, irrigation pasture, and cow brushing) were counted together.

**Table 2** Average electrical energy consumptions, in kWh month$^{-1}$, associated with different dairy farm activities and herd sizes.

| Month | Lighting | | Milking | | Milk cooling and refrigeration | | Cleaning and disinfection | | Miscellaneous | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 100 cows | 150 cows | 100 cows | 150 cows | 100 cows | 150 cows | 100 cows | 150 cows | 100 cows | 150 cows |
| **1** | 2.9 | 3.7 | 19.4 | 25.2 | 23.7 | 30.8 | 8.6 | 11.2 | 17.2 | 22.4 |
| **2** | 3.1 | 4.0 | 20.8 | 27.1 | 25.4 | 33.1 | 9.3 | 12.0 | 18.5 | 24.1 |
| **3** | 2.7 | 3.6 | 18.2 | 24.6 | 22.3 | 30.0 | 8.1 | 10.9 | 16.2 | 21.9 |
| **4** | 2.5 | 3.3 | 17.2 | 22.0 | 21.0 | 26.9 | 7.6 | 9.8 | 15.3 | 19.6 |
| **5** | 2.5 | 3.2 | 16.9 | 21.5 | 20.6 | 26.3 | 7.5 | 9.5 | 15.0 | 19.1 |
| **6** | 2.2 | 2.9 | 14.7 | 19.3 | 17.9 | 23.5 | 6.5 | 8.6 | 13.0 | 17.1 |
| **7** | 2.2 | 2.8 | 14.6 | 18.9 | 17.9 | 23.1 | 6.5 | 8.4 | 13.0 | 16.8 |
| **8** | 2.6 | 3.5 | 17.8 | 23.7 | 21.7 | 28.9 | 7.9 | 10.5 | 15.8 | 21.0 |
| **9** | 3.4 | 4.2 | 23.2 | 28.2 | 28.4 | 34.5 | 10.3 | 12.5 | 20.6 | 25.1 |
| **10** | 3.4 | 4.1 | 22.9 | 28.0 | 28.0 | 34.2 | 10.2 | 12.4 | 20.3 | 24.8 |
| **11** | 3.5 | 4.4 | 23.4 | 29.8 | 28.6 | 36.4 | 10.4 | 13.2 | 20.8 | 26.5 |
| **12** | 3.3 | 4.3 | 22.3 | 29.1 | 27.2 | 35.6 | 9.9 | 12.9 | 19.8 | 25.9 |

On average, the following percentages of electricity were consumed annually in dairy farms of different herd sizes: 4% for lighting, 27% for milking, 33% for milk cooling/refrigeration, 12% for cleaning/disinfection, and 24% for miscellaneous. The pattern of electrical energy usage varied subtly across seasons for specific activities. For instance, the lighting duration in areas such as the milking parlor, milk tank room, and cow buildings was shorter in summer than in winter, influenced by the natural photoperiod.

The average daily variations in electricity generated by the simulated photovoltaic systems located in the municipalities of Lavras and Paracatu are presented in Figure 4 and Figure 5, respectively, showing the energy consumed by the dairy farm activities for 100 and 150 cows.

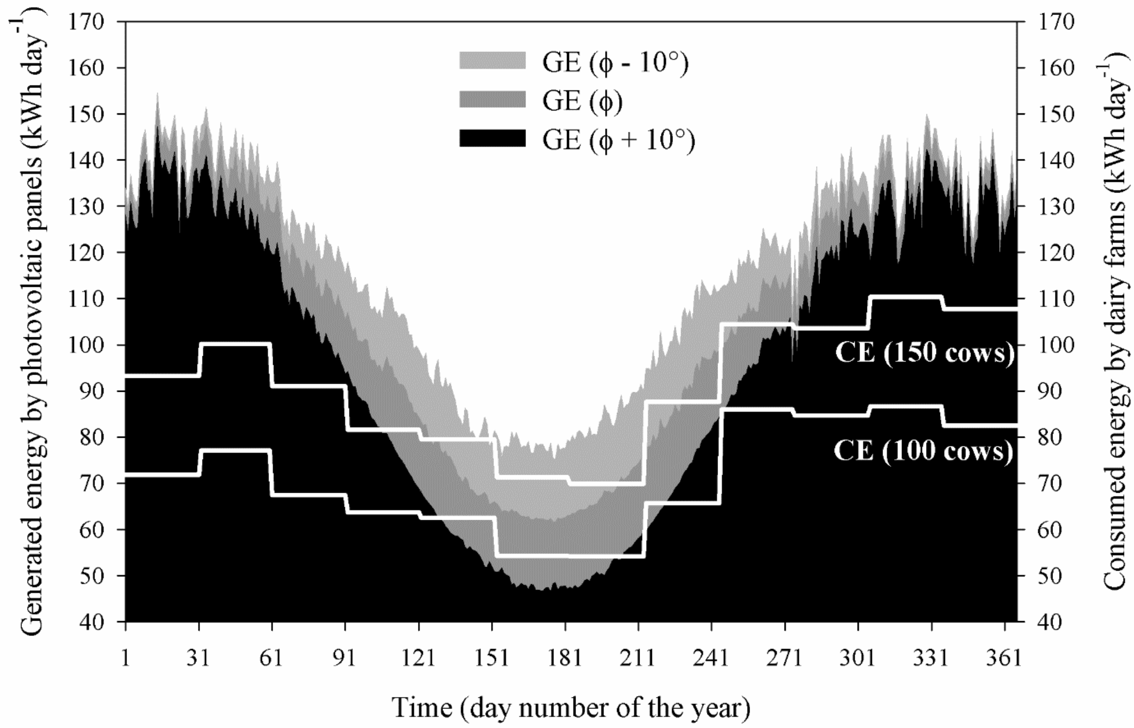


**Figure 4** Daily variations in electrical energy generation for the different tilt angles and electricity consumptions for the distinct herd sizes (100 and 150 cows) in the municipality of Lavras (21.75° S), Minas Gerais State, Brazil.

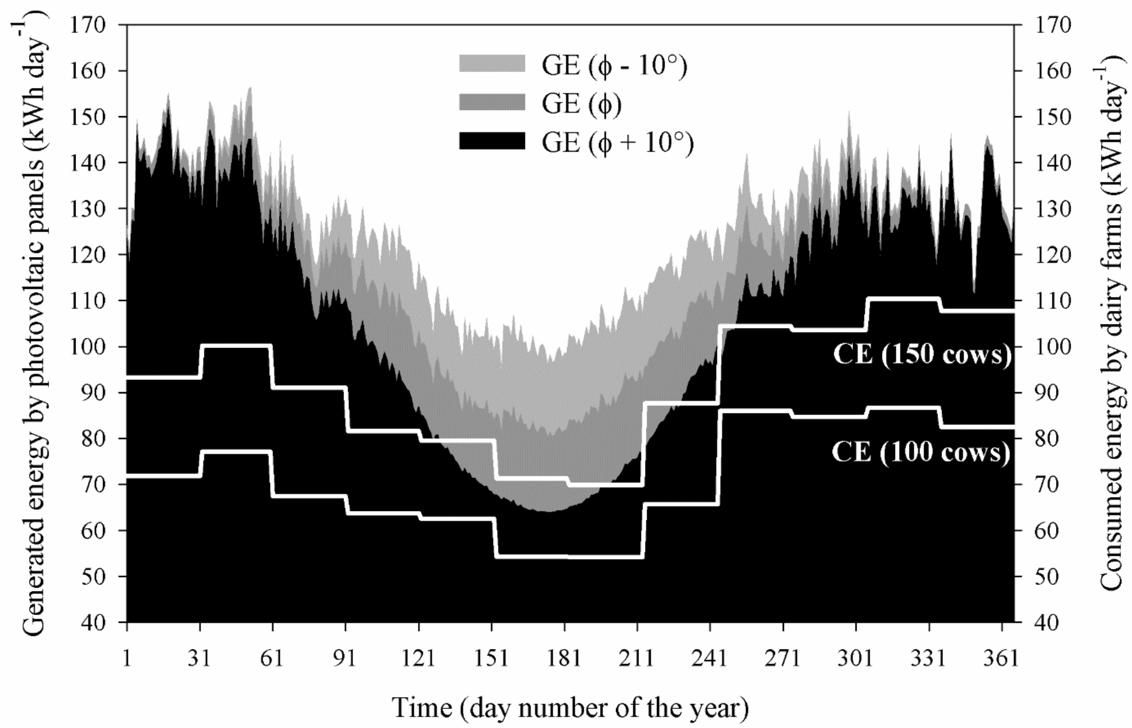


**Figure 5** Daily variations in electrical energy generation for the different tilt angles and electricity consumptions for the distinct herd sizes (100 and 150 cows) in the municipality of Paracatu (17.24° S), Minas Gerais State, Brazil.

The patterns of energy generation verified in this study agree with [27], who affirmed that increasing the tilt inclination angle of panels causes major losses in photovoltaic system performances. The authors investigated a photovoltaic system installed in Douala (Cameroon), noting that the variation in electricity production with north and south orientations differs at the same tilt angle, increasing for the north orientation and decreasing for the south orientation, depending on the time of year. However, the improvement in the efficiency of a photovoltaic system, resulting from increments and decrements in the tilt angle of the panels, is limited to a small range. Several authors have proven that panels' annual optimum tilt angles are close to the latitude of the studied locations. Annual optimum tilt angle in Karachi (Pakistan) was closer to its latitude value [28]. Similar results were obtained for 12 locations in the western Himalayan hilly state of Himachal Pradesh (India) [22]. On the other hand, for the Highveld region of South Africa the recommendation was to mount the photovoltaic panels with a tilt angle of latitude minus 10° during the summer season [29]. When cities of different Brazilian regions were analyzed, the optimal tilt angle was equal to or approximately 9° higher than the latitude value [30], while tilt angles approximately 9.5° less than latitude were indicated as optimal for both Ottawa and Toronto (Canada) [31].

When considering the consumed energy by dairy farm activities, demands vary with different herd sizes, even though most operations are similar. According to [10], the main variables influencing electricity demands are the equipment technologies and the microclimate conditions. Energy consumption per dairy cow obtained in this study (0.47-0.87 kWh $cow^{-1}$ $day^{-1}$) was similar to those found by [32, 33], who estimated dairy farm demands between 0.68-1.10, and 0.49-2.49 kWh $cow^{-1}$ $day^{-1}$, respectively.

For the municipality of Lavras (Figure 4), the photovoltaic panel area of 170 $m^2$ was sufficient to supply 100% of the electricity demands required by 100 cows when using the tilt angle of panels equal to the latitude or the latitude - 10°. For this same municipality and farms with 150 cows, the simulated panel area could meet 100% of the electrical energy demand only with tilt angle equal to the latitude - 10°, except for three days in May (24, 29, and 30). On the other hand, analysis of Paracatu (Figure 5) showed that all tilt angles tested were sufficient to meet 100% of the electricity demand of the dairy farms with 100 cows. For larger herd size (150 cows), the electrical energy generated with a tilt angle equal to the latitude + 10° was insufficient to supply the electricity demand from May 6 to July 17, August 11-15, and September 1-7.

These results are associated with the higher electrical energy generation verified in Paracatu, which exceeded that in Lavras by 9.0, 10.0, and 10.6 kWh $day^{-1}$ on average, when using the tilt angles of panels equal to the latitude - 10°, latitude, and latitude + 10°, respectively. The differences were more evident from April to September and can be justified by the geographic location of the municipalities and the typical cloudiness conditions verified from the historical databases of sunshine duration.

In relation to the best results obtained with the tilt angle of panels equal to the latitude - 10°, other studies also indicated that the optimum fixed tilt angle might differ from the latitude value [28, 34]. The results obtained in this study agree with [24, 35], who found optimum annual fixed tilt angles equal to latitude - 10° in Spain and England, respectively. Furthermore, [31] recommended that photovoltaic panels be tilted from 7° to 12° less than the local latitudes in Canada. Many conditions affect the optimal tilt angle of fixed photovoltaic panels for individual locations, including rainfall, cloudiness, snow, air temperature, dust, and shading [29]. For this, research must be performed to determine the optimum tilt angles of panels for specific locations [28].

The use of long-term meteorological datasets is important in considering inter- and intra-annual variabilities of global solar radiation and, consequently, in electrical energy generation. Many authors have evaluated the impact of the tilt angle of photovoltaic systems on energy generation over several years by using long-term meteorological databases for various locations, such as Brazil [10], countries with different climates [36], United Kingdon [37], and Europe [38]. These studies led to more consistent results and helped better understand global solar radiation trends and patterns across the studied locations.

Aiming to compensate for the differences in the electricity generation between Paracatu and Lavras for the same herd size, it is indicated that the number of panels in the photovoltaic system should be increased. This procedure is also recommended to enhance electricity generation using the different tilt angles considered in this study. However, this solution will impact the costs of implantation and maintenance, requiring an economic analysis that compares the tax credits received by the dairy farm for each kWh injected in the cable aerial network of the electrical energy company with the values paid for each kWh consumed by the dairy farm activities [6, 7]. Another possibility is to use the tax credits resulting from the electrical energy surplus obtained during the months with higher electricity generation. However, this purpose will be financially favorable only if the tax credits are sufficient to pay for the electricity consumption from the external energy network, as shown by [5].

Additionally, regardless of municipality or system configuration, energy consumption peaks can occur, mainly during the summer months, but also in the late morning and early afternoon when the air temperature is more elevated [4]. Specifically, the dairy farm equipment and processes can demand more electricity, not coinciding with the periods of increased energy generation, even the simulations showing long periods with electrical energy generation equal or greater than the average demand, as demonstrated by [8, 11]. According to [9], this can be addressed using the external energy network supplying electricity to meet the excess demand, considering that the photovoltaic system is grid-connected. The external supply is generally compensated in other periods by injecting the electrical energy surplus generated by the photovoltaic system into the external network. According to [4], well-designed photovoltaic systems have the potential to meet a large part of the peak demands of different buildings, representing an alternative for enhancing the stability of the electricity grid.

The average monthly differences (deficit or surplus) between the electricity produced by the photovoltaic systems and the electrical energy consumption of dairy farms located in the municipalities of Lavras and Paracatu, for the distinct tilt angles of panels and herd sizes, are presented in Figure 6.

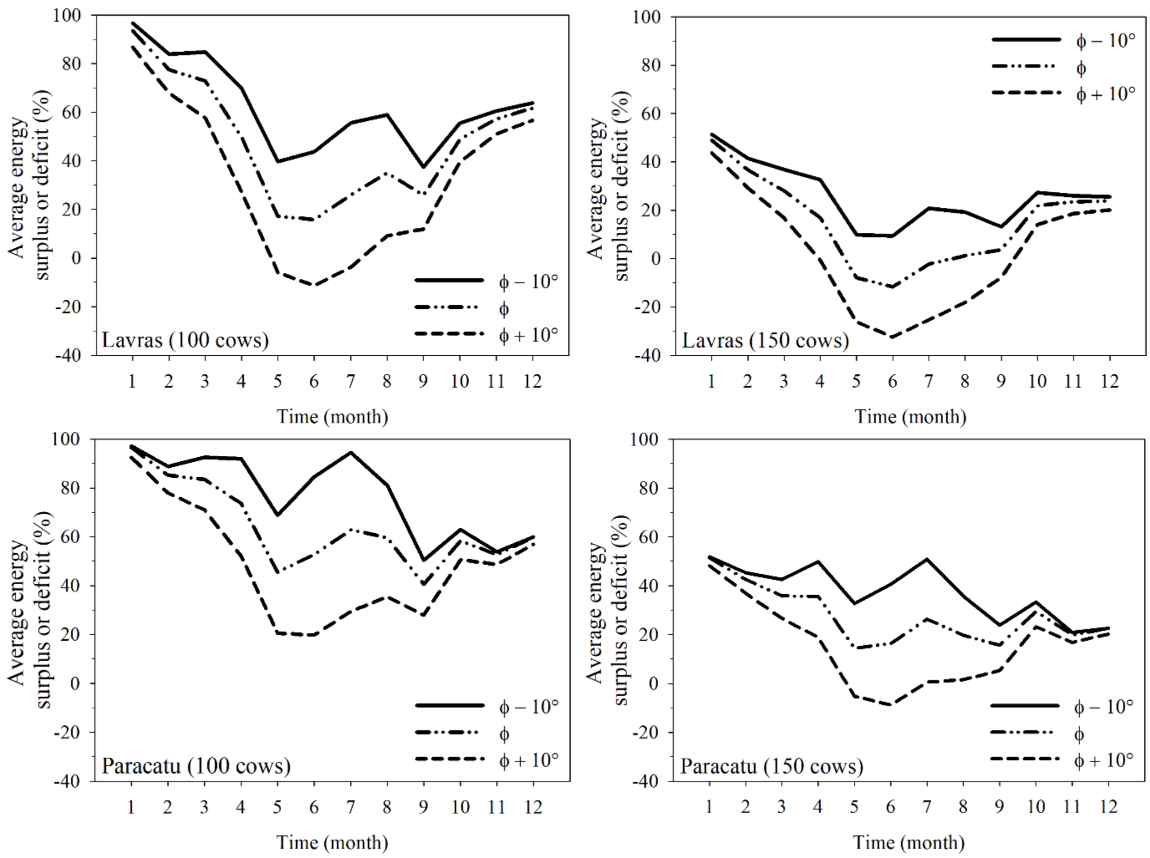


**Figure 6** Monthly differences (deficit or surplus) between the electrical energy generation and the electricity consumption for the different tilt angles and herd sizes (100 and 150 cows) in the municipalities of Lavras (21.75° S) and Paracatu (17.24° S), Minas Gerais State, Brazil.

Confirming the results observed in Figure 4 and Figure 5, the use of a tilt angle of panels equal to the latitude - 10° led to higher electrical energy generation and consequently elevated energy surplus, followed by a tilt angle equal to the latitude. The tilt angle equal to the latitude + 10° resulted in more electricity deficits, mainly when the herd size of 150 cows was evaluated. Also, the municipality of Paracatu presented greater surplus generation potential than Lavras. For all simulated scenarios, the smallest energy surplus values and most deficits were verified from the end of summer (March) to mid-spring (October). During these months, the daytime period decreases until the beginning of winter (June 22), resulting in lower global solar radiation values and, consequently, electricity generated. On the other hand, electricity consumption for milk cooling and refrigeration is lower due to the decrease in air temperature, although the buildings' artificial lighting time increases with the reduction of natural photoperiod. Furthermore, for all simulated scenarios, November, December, January, February, March, April, and July promoted elevated energy surplus values. Except for July, these months correspond to the late spring, summer, and early autumn in the Southern Hemisphere. The greater availability of solar radiation leads to large electricity generation by the photovoltaic system.

When considering the daily data, there were no energy deficits for the municipality of Paracatu (100 cows) when using the tilt angles evaluated in this study. The maximum energy surplus was verified for the tilt angle equal to the latitude - 10° (115.1% in January), while the minimum value was obtained with the tilt angle equal to the latitude + 10° (8.5% in May). For Paracatu (150 cows), the energy deficits occurred only when using the tilt angle equal to the latitude + 10°, reaching a maximum value of -14.7% in May and a minimum of -5% in June. The tilt angle equal to the latitude + 10° also led to energy deficits in Lavras (100 cows), with maximum and minimum values of -18.7% (in May) and -4.9% (in June), respectively. When analyzing dairy farms in Lavras (150 cows), there were energy deficits using all tilt angles tested in this study, with the tilt angle equal to the latitude - 10°as the most effective. For this tilt angle and 150 cows in Lavras, the maximum energy surplus was verified in January (65.6%), while the minimum value occurred in June (5.3%).

The approach presented in this study is suitable for other dairy farms, agricultural and urban buildings. As shown in the results, the optimal tilt angle of panels will depend on the location's geographic coordinates, meteorological conditions, aerosol, shading, and others. The technology and efficiency of the equipment used in each building and the photovoltaic system will also contribute to differences.

## 4. Future Studies and Recommendations

Since many conditions and variables affect the performance of photovoltaic systems, additional research is suggested to determine the optimum tilt angles and estimate incident solar radiation on panels using other methodologies. This includes the use of artificial neural networks, which can solve non-linear and complex problems and appear as an efficient tool for determining optimal tilt angles in photovoltaic systems [39]. Another possibility is applying probabilistic and error analysis projections to estimate different weather conditions and to find optimal tilt angles based on these simulations [37]. Several optimization techniques can be combined and compared to identify the optimal tilt angle, such as genetic algorithms, simulated annealing techniques, and particle swarm optimization [15]. These algorithms are valuable in constructing, designing, understanding, and maintaining different engineering systems.

The use of solar tracking systems to obtain the maximum kWh $cow^{-1}$ $day^{-1}$ is also highly recommended for future studies. For this, the optimum tracking mechanism and the algorithm must be evaluated to maximize energy production while ensuring the durability and reliability of the photovoltaic system [36].

This study considered a well-designed grid-connected photovoltaic system with new components. However, polycrystalline photovoltaic panels have a lifetime of 25 years on average, and the conversion efficiency of solar radiation into electrical energy is reduced over this period, mainly due to the cell encapsulation, contact corrosion, formation of conductive channels to the grounded frame, and moisture penetration. According to [40], after 10 years of operation, the frequency of failures of the panels rises considerably, with systems installed in tropical regions having further reduced real lifetime due to the climate conditions. Thus, after the lifetime, panels frequently must be changed or refurbished [9]. Other factors that can harm the photovoltaic system's efficiency include increased panel temperature, ultraviolet radiation [3, 15], and natural and artificial obstacles that could affect the solar radiation incidence on the panels [30]. Specifically, subtropical and tropical regions, such as Lavras and Paracatu, are characterized by elevated atmospheric aerosols in the dry season, mainly due to soil dust and soot from biomass burning. Additionally, [27] reported that dust accumulation on photovoltaic panels can cause losses in energy generation of up to 7% per month, recommending cleaning the panels periodically.

## 5. Conclusions

In this study, different geographic locations and meteorological conditions (solar radiation, cloudiness, day length, and air temperature) affected the performances of the photovoltaic systems, with dairy farms located at lower latitudes having greater energy generation potential. For both Brazilian municipalities (Lavras and Paracatu), best results were verified when photovoltaic panels were tilted 10° less than the local latitudes. For the different municipalities and herd sizes (100 and 150 cows) studied, greater energy surplus values were found from late spring to early autumn. During this period, the higher availability of solar radiation leads to larger electricity generation by the photovoltaic systems, meeting the elevated electrical energy demand of the dairy farm activities. High energy surplus values were also verified during midwinter, when the lower energy consumption compensated for the reduced availability of solar radiation for dairy activities, such as milk cooling and refrigeration. Long-term meteorological datasets were essential to capture inter- and intra-annual variabilities in energy generation, leading to more consistent results and a better understanding of trends and patterns in solar power generation over the studied periods.

## Acknowledgments

The authors would like to thank the National Institute of Meteorology (INMET) of Brazil for providing the weather data.

## Author Contributions

Conceptualization, data curation, methodology, and writing (original draft): Antonio José Steidle Neto. Data analysis and writing (review and editing): Daniela de Carvalho Lopes.

## Competing Interests

The authors have declared that no competing interests exist.

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