Engenharia Agrícola

ISSN: 1809-4430 (on-line)

www.engenhariaagricola.org.br

Special Issue: Energy in Agriculture

Scientific Paper

Doi: http://dx.doi.org/10.1590/1809-4430-Eng.Agric.v43nepe20220143/2023

MATHEMATICAL MODELING OF GREEN TARIFF ELECTRICITY BILLING IN A LAYER POULTRY FARM BASED ON CONSUMPTION INDICATORS

Monclar N. Christovão[1], Camila P. Cremasco[2], Mario Mollo Neto[2], Luís R. A. Gabriel Filho[2*]

[2*]Corresponding author. São Paulo State University (UNESP), School of Science and Engineering/Tupã - SP, Brazil.
E-mail: gabriel.filho@unesp.br | ORCID ID: https://orcid.org/0000-0002-7269-2806

KEYWORDS

electricity billing, green hourly tariff, electricity bill simulation software, load factor, power factor.

ABSTRACT

The increasing electricity consumption, inflated costs, and environmental restrictions drive the need for more efficient energy usage and the development of energy conservation programs. Many farms in Brazil produce their animal feed by crushing grains and cereals using electric motor-equipped devices. However, these motors are often oversized and operate during peak times, leading to increased production costs. This study aimed to mathematically model electricity billing under the green tariff (group A) for an egg production farm. The model incorporated mathematical equations based on selected electrical parameters such as load, power factors, energy demand, and active consumption. The Mathematica software was used to implement the proposed model. The farm provided the past twelve electricity bills, which were inputted into the software, generating three-dimensional surface graphics and contour maps. These visualizations revealed an inversely proportional relationship between bill prices and power/load factor indicators. This study concludes that the presented methodology can be employed by agribusiness companies to assess performance, explore alternatives, avoid potential fines, and optimize energy consumption.

INTRODUCTION

In Brazil, the electricity bill for large agro-industries includes charges for demand and consumed energy. The demand charge is calculated based on the average active power consumed every 15 minutes during the billing period (nearly 30 days), using the highest average value as the billing demand in kilowatts (kW). The energy consumed in kilowatt-hours (kWh) is the sum of the active power consumed over the billing period (Park et al., 2017).

The contract demand represents the required active power in kilowatts (kW) that the electricity provider must supply continuously to the customer's delivery point, as specified in the power purchase agreement. Regardless of whether the full contracted power is used or not, the customer must pay the bill in full.

Electricity demand varies based on seasons and hours, with peak demand usually occurring in the late afternoon and early evening when electricity tariff prices are extremely high (Wang & Li, 2016). Reducing peak loads helps decrease costs with extra energy capacity and contributes to a decrease in power plants' operating costs and wholesale electricity prices (Nezamoddini & Wang, 2017).

Research highlights the importance of energy studies in agribusiness companies. Many studies have examined conventional electricity generation and alternative sources such as that of Canossa et al. (2018). Studies of electricity in agribusiness have approached biomass production (Dadario et al., 2023, Dinnebier et al., 2021; Ribeiro et al., 2020), farm electrification (Soofi et al., 2022), food and agribusiness enterprises (Khan et al., 2022; Rahman et al., 2022), and energy consumption with agricultural growth (Raeeni et al., 2019).

[1] São Paulo Federal Institute of Education, Science, and Technology (IFSP)/Tupã - SP, Brazil.
[2] São Paulo State University (UNESP), School of Science and Engineering/Tupã - SP, Brazil.

Area Editor: Flavia Lucila Tonani Siqueira
Received in: 8-29-2022
Accepted in: 6-19-2023

Furthermore, some studies have proposed alternative sources of electricity such as renewable ones. These studies include several applications such as meteorological variables (Cunha et al., 2021a and Cunha et al. 2021b), photovoltaic systems (Gabriel Filho et al. 2012 and Gabriel Filho et al. 2016), wind power systems (Nazaré et al., 2020), and hybrid power systems (Seraphim et al., 2014).

Agribusiness companies face multiple electricity consumption issues, including power oscillations throughout the day caused by simultaneous operation of machines leading to peak loads and idle periods. This results in high contract demands or fines for exceeding the agreed limit, and companies still encounter challenges when machines operate at full capacity during expensive peak hours (Regnier & Winters, 2013). Excessive consumption of reactive energy leads to fines for low Power Factor (PF). Furthermore, installing electric motors with higher power capacity than necessary, using outdated electric start systems, and initiating simultaneous starts of machines and equipment connected to electric motors contribute to consumption challenges. Additionally, machines and equipment starting at full load capacity exacerbate the issues faced by agribusiness companies.

To address these challenges, it is important to research computer programs that monitor energy consumption, track indexes, and electrical magnitudes to promote conscious and efficient energy usage. In this sense, this study developed a mathematical model for electricity billing in a layer poultry farm using the green tariff type, considering load factor (LF) and power factor (PF) indexes. Three-dimensional surface graphs and contour maps were created to visualize lower billed amounts in cooler colors and higher bills in warmer colors, exploring possible LF and PF combinations for more cost-effective bills.

MATERIAL AND METHODS

This study examined the electricity consumption efficiency of a layer poultry farm in Bastos, São Paulo State, Brazil. The farm manager provided 12 electricity bills spanning from August 2018 to July 2019 specifically for the sector known as the Egg Tray Industry.

The farm consists of poultry houses catering to various growth stages, including chicks and laying hens from different strains (white or brown shelled eggs). These houses contain high-power machines responsible for tasks such as feeding the poultry. In particular, the machines are installed in the egg cleaning, vertical and horizontal conveyor belts, selection, packaging, and storage houses.

The farm utilizes automated machines for egg collection, cleaning, and classification based on weight, as well as for packaging them into different types of packages. Additionally, the farm processes its own poultry feed, which maintains a nearly constant formulation with minor variations in components depending on the age of the poultry. The primary components of the feed include corn and soybeans.

Electricity Billing

The electricity bill for a Consumer Unit (CU) is calculated based on the highest power demand assessed every 15 minutes within the billing period, typically around 30 days. This highest demand value, along with the consumed energy, contributes to the total bill. The bill comprises the highest value between the contract demand and the measured demand (in kW), while the consumed energy is the sum of the active power during the period (in kWh). Each item obtained from these calculations is summed to determine the monthly bill.

To calculate the Load Factor (LF) values, which are not provided in the monthly bills but required for eqs (3) and (4), [eq. (1)] is used:

$$LF = \frac{AEEm}{t.ADm} \quad (1)$$

Wherein:

t: the time interval in hours (h);

LF: the load factor for a CU within the time interval "t";

$AEEm$: the measured active electrical energy in kWh,

ADm: the measured active power demand in kW; and

Average Power Factors (PF_A) are calculated monthly using [eq. (2)] to be inserted into eqs (3) and (4):

$$PF_A = PF_R \frac{AEEm}{E_{RE} + AEEm} \quad (2)$$

Wherein:

PF_A: the average PF for the CU calculated for the billing cycle;

$AEEm$: the amount of measured active energy in kWh during the billing period;

PF_R: the Reference PF, standardized by utilities at 92%, and

E_{RE}: the amount of active energy in kWh corresponding to the excess consumption of reactive energy.

Green Hourly Tariff Billing

There is a single green tariff for power demand (R$/kW) and two types of green tariffs for energy consumption: one for peak hours (R$/kWh) and another for off-peak hours (R$/kWh).

The billing for the Consumer Unit (CU) is calculated based on the company's monthly Power Factor (PF) using eqs (3) and (4) as described below.

For $0 < PF < 0.92$:

$$B = \frac{0.92}{PF_p}\left(TC_p + \frac{TD}{730\ LF}\right)C_p + \frac{0.92}{PF_{op}}\left(TC_{op} + \frac{TD}{730\ LF}\right)C_{op} \quad (3)$$

For $0.92 \le PF \le 1$:

$$B = \left(TC_p + \frac{TD}{730\ LF}\right)C_p + \left(TC_{op} + \frac{TD}{730\ LF}\right)C_{op} \quad (4)$$

Wherein:

B: the amount, in reais (R$), of the total electricity billing for CU in the billing cycle;

PF_p: the PF at peak hours;

PF_{op}: the PF at off-peak hours;

LF: load factor;

C_p: the consumption of active energy at peak hours (kWh) pertinent to the billing cycle;

C_{op}: the consumption of active energy at off-peak hours (kWh) pertinent to the billing cycle;

TC_p: the tariff for consumption of active energy (R$/kWh) at peak hours;

TC_{op}: the tariff for consumption of active energy (R$/kWh) at off-peak hours, and

TD: the tariff for active demand per kilowatt-hour (R$/kWh).

Mathematical Modeling for Billing

We used Mathematica software to analyze electricity billing by creating three-dimensional surfaces and contour maps. Equations (3) and (4) were entered into the software to generate load and power hyperboloids. The graphs represent the monthly calculated LF and PF values at each point.

RESULTS AND DISCUSSION

Below we provide an overview of the primary characteristics obtained from the analysis of 12 electricity bills issued to an egg farm:

- Classification: Rural class and Rural subclass, specifically categorized as Rural Agriculture;
- Connection: three-phase;
- Voltage: 11,400 Volts;
- Tax exemption: ICMS (Service and Goods Circulation Tax);
- Subgroup: A4;
- Contract demand: 360 kW;
- Tariff selection: green hourly tariff.

The equations representing the tariff type chosen by the company were modified using the following substitutions: $a_1 = TC_p$, $a_2 = TC_{op}$, $b = TD$, $c_1 = C_p$, and $c_2 = C_{op}$. By applying these substitutions, [eq. (5)] was derived to calculate the billing amount It is important to note that this formulation relies on the company's monthly Power Factor (PF) as described by Cremasco et al. (2010).

$$g(x,y) = \begin{cases} \frac{0.92}{x}\left(a_1 + \frac{b}{730y}\right)c_1 + \frac{0,92}{x}\left(a_2 + \frac{b}{730y}\right)c_2, & if\ 0 < x < 0.92 \\ \left(a_1 + \frac{b}{730y}\right)c_1 + \left(a_2 + \frac{b}{730y}\right)c_2, & if\ 0.92 \le x \le 1 \end{cases} \quad (5)$$

Subsequently, we gathered the main data from the 12 electricity bills of the egg farm. We observed an additional fee for excessive consumption of reactive energy, solely in the month of March (PF below 92%). By utilizing [eq. (2)], we determined that the PF_A for the farm during that period was 91%.

In the remaining months, as there were no charges for exceeding the consumption of reactive energy, we assumed a default PF of 92% for the electricity bills. It is important to note that we were aware of the presence of capacitor banks employed to correct PF.

The tariff and consumption averages were calculated as follows:

a_1: $TCa\_peak = 1.259407$

a_2: $TCa\_off\_peak = 0.280454$

b: $TDa = 13.376944$

c_1: $Ca\_peak = 3556.5$

c_2: $Ca\_off\_peak = 112282$

Wherein:

x: PF;

y: LF,

$g(x,y)$: billing.

Seeking to show an overview of all billing possibilities against the values of PF and LF, three-dimensional surfaces and contour maps of the models presented here were established (FIGURE 1). Also, to encompass all PF and LF values measured in the months under study, we considered (FIGURE 2) a range between 0.80 and 1 for the PF ($0.80 \le PF \le 1$), and between 0.40 and 0.60 for the LF ($0.80 \le LF \le 1$). We used the following command lines in the Mathematica software for the generation of the graphics results:

```
a1=1.259407; a2=0.280454; b=13.376944; c1=3556.5; c2=112282;
g[x_,y_]:=(0.92/x)*(a1+b/(730*y))*c1+(0.92/x)*(a2+b/(730*y))*c2/; 0<x<=0.92
g[x_,y_]:=(a1+b/(730*y))*c1+(a2+b/(730*y))*c2/; 0.92<x<=1

Plot3D[g[x,y], {x,0,1}, {y,0,1}, PlotPoints->100, ColorFunction->"Rainbow",
AxesLabel->{"PF","LF","B(R$)"}, LabelingSize->100, Mesh->10, PlotLegends ->
BarLegend[Automatic, LegendMarkerSize->{20, 200}, LabelStyle->{FontSize -> 14}],
ClippingStyle->None, BaseStyle->{FontSize->14}]

ContourPlot[g[x,y], {x,0,1}, {y,0,1}, PlotPoints->100, ColorFunction->"Rainbow",
Frame->False, Axes->True, AxesLabel->{"PF","LF"}, BaseStyle->{FontSize -> 20}, Mesh-
>10, PlotLegends->BarLegend[Automatic, LegendMarkerSize->{20, 200}], ClippingStyle-
>None]
```

```
Plot3D[g[x,y], {x,0.8,1}, {y,0.4,0.6}, PlotPoints->100, ColorFunction->"Rainbow",
AxesLabel->{"PF","LF","B(R$)"}, LabelingSize->100, Mesh->5, PlotLegends-
>BarLegend[Automatic, LegendMarkerSize->{20, 200}, LabelStyle->{FontSize->14}],
ClippingStyle->None, BaseStyle->{FontSize->14}]

ContourPlot[g[x,y], {x,0.8,1}, {y,0.4,0.6}, PlotPoints->100, ColorFunction-
>"Rainbow", Frame->False, Axes->True, AxesLabel->{"PF","LF"}, BaseStyle->{FontSize ->
20}, Mesh->10, PlotLegends->BarLegend[Automatic, LegendMarkerSize->{20, 200}],
ClippingStyle->None]
```

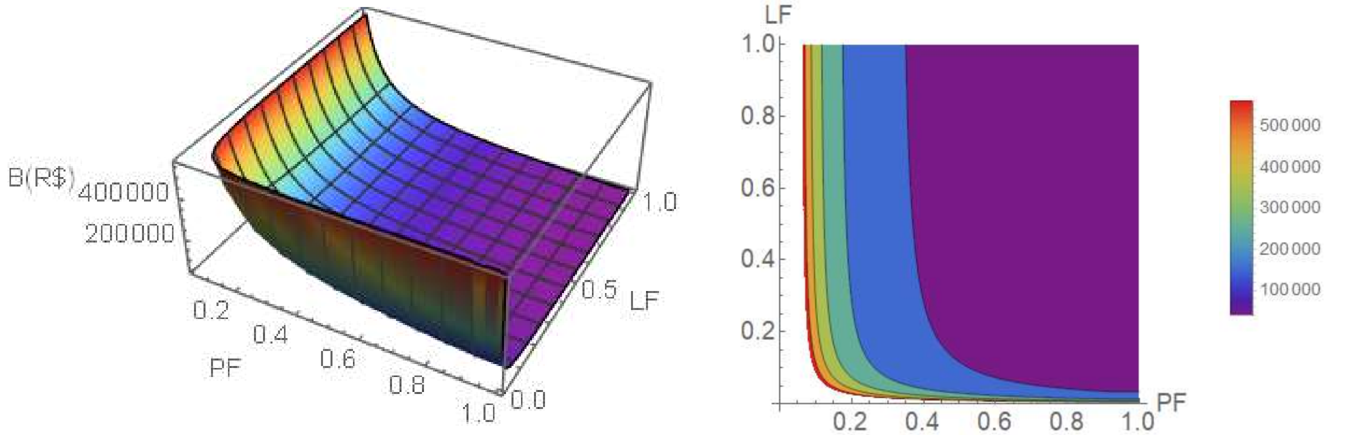

FIGURE 1. Surface and contour map of the Hyperboloid representing the billing index for values of $\boldsymbol{PF}$ and $\boldsymbol{LF}$ between 0 and 1.

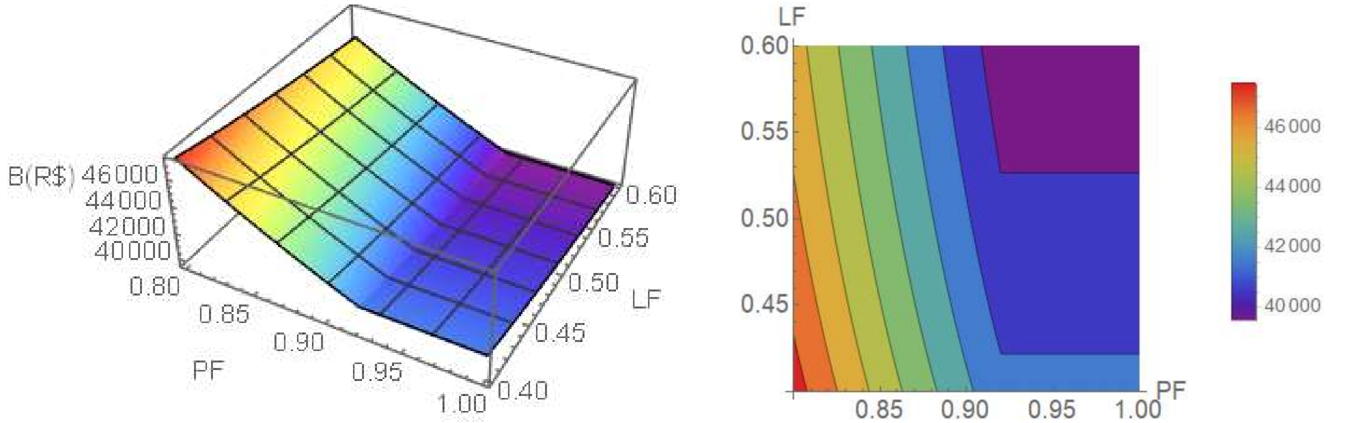

FIGURE 2. Surface and contour map of the Hyperboloid representing the billing index for the region encompassing all $\boldsymbol{PF}$ and $\boldsymbol{LF}$ values measured in the months under study, i.e. $(\boldsymbol{PF}, \boldsymbol{LF}) \in [\mathbf{0.80}, \mathbf{1}] \times [\mathbf{0.80}, \mathbf{1}]$.

In both graphical simulations (FIGURE 1 and FIGURE 2), by analyzing the colors and tones in the graphs, we can observe that cooler colors correspond to lower electricity bill amounts, while warmer colors indicate higher amounts. It is important to note that as the PF values approach one (1), the electricity bill amount decreases. Similarly, there is a decrease in the bill amount as the LF values increase. Therefore, we can conclude that the electricity bill amount is inversely proportional to the power and load factor indexes.

Based on the findings, two procedures can be implemented to achieve a reduction in the electricity bill amount. The first procedure involves the installation of properly calculated capacitive cells or capacitor banks within the company's electrical system, thereby maintaining PF values between 92% and 100%. The second involves increasing the LF index towards a value close to one (1) by implementing specific measures. These measures include utilizing start ramps for electric motors, avoiding simultaneous start-up of machinery and electric motors, identifying, and adjusting the operation schedules of machines and equipment to align with periods of lower power demand, and rescheduling the operation of machinery and electric motors throughout the day to mitigate simultaneous operations.

By implementing these procedures, the managers of the egg farm can effectively reduce the impact on monthly bills, exercise greater control over their demand contracts, and minimize excessive consumption of reactive energy within their production units.

CONCLUSIONS

The proposed mathematical modeling for analyzing electricity bills in agribusiness companies, using consumption indicators and bill simulations, offers valuable insights for technicians and managers to reduce their electricity expenses by improving the LF and PF indexes close to 1.

We generate three-dimensional surface graphs and contour maps based on data from an egg farm. The model allows us to calculate electricity billing considering both load and power factors, showing effectively the significance of corrective measures to excessive consumption of reactive energy, either independently or in conjunction with conscious operational practices for machinery and electric motors. Implementing such measures assists in reducing electricity costs while maintaining energy consumption.

By utilizing the proposed mathematical modeling, farm managers can accurately assess and validate their electricity bills, minimizing the risk of incurring fines and penalties in the future.

REFERENCES

Canossa JH, Bonini Neto A, Alves DA, Putti FF, Gabriel Filho LRA (2018) Development of an interactive program to study of the continuation power flow. IEEE Latin America Transactions 16(4): 1227-1235. http://doi.org/10.1109/TLA.2018.8362161

Cremasco CP, Gabriel Filho LRA, Cataneo A (2010) Metodologia de determinação de funções de pertinência de controladores fuzzy para a avaliação energética de empresas de avicultura de postura. Energia na agricultura 25(1): 21-39. http://doi.org/10.17224/EnergAgric.2010v25n1p21-39

Cunha AC, Gabriel Filho LRA, Putti FF (2021a) Performance and estimation of solar radiation models in state of Minas Gerais, Brazil. Modeling Earth Systems and Environment 7(1): 603-622. http://doi.org/10.1007/s40808-020-00956-x

Cunha AC, Gabriel Filho LRA, Tanaka AA, Góes BC, Putti FF (2021b) Influence of the estimated global solar radiation on the reference evapotranspiration obtained through the Penman-Monteith FAO 56 method. Agricultural Water Management 243: 106491. http://doi.org/10.1016/j.agwat.2020.106491

Dadario N, Gabriel Filho LRA, Cremasco CP, Santos FA, Rizk MC, Mollo Neto M (2023) Waste-to-Energy Recovery from municipal solid waste: global scenario and prospects of mass burning technology in Brazil. Sustainability 15(6): 5397. http://doi.org/10.3390/su15065397

Dinnebier HCF, Matthiensen A, Michelon W, Tápparo DC, Fonseca TG, Favretto R, Steinmetz RLR, Treichel H, Antes FG, Kunz A (2021) Phycoremediation and biomass production from high strong swine wastewater for biogas generation improvement: An integrated bioprocess. Bioresource Technology 332:125111. http://doi.org/10.1016/j.biortech.2021.125111

Gabriel Filho LRA, Seraphim OJ, Caneppele FL, Cremasco CP, Putti FF (2016) Variable analysis in wind photovoltaic hybrid systems in rural energization. IEEE Latin America Transactions 14(12): 4757-4761. http://doi.org/10.1109/TLA.2016.7817007

Gabriel Filho LRA, Viais Neto DS, Cremasco CP, Seraphim OJ, Caneppele FL (2012) Mathematical analysis of maximum power generated by photovoltaic systems and fitting curves for standard test conditions. Engenharia Agrícola 32(4): 650-662. http://doi.org/10.1590/S0100-69162012000400004

Khan W, Ali T, Dhamija A (2022) Perceived obstacles and performance of food and agribusiness enterprises: implications for urban and rural entrepreneurship development. Journal of Industrial Integration and Management 17:1-18. http://doi.org/10.1142/S2424862221500287

Nazaré G, Castro R, Gabriel Filho LRA (2020) Wind power forecast using neural networks: Tuning with optimization techniques and error analysis. Wind Energy 23(3): 810-824. http://doi.org/10.1002/we.2460

Nezamoddini N, Wang Y (2017) Real-time electricity pricing for industrial customers: Survey and case studies in the United States. Applied Energy 195(1):1023-1037. http://doi.org/10.1016/j.apenergy.2017.03.102

Park YG, Park JB, Kim N, Lee KY (2017) Linear formulation for short-term operational scheduling of energy storage systems in power grids. Energies 10(2): 207. http://doi.org/10.3390/en10020207

Raeeni AAG, Hosseini S, Moghaddasi R (2019) How energy consumption is related to agricultural growth and export: An econometric analysis on Iranian data. Energy Reports 5:50-53. http://doi.org/http://doi.org/10.1016/j.egyr.2018.11.005

Rahman MM, Khan I, Field DL, Techato K, Alameh K (2022) Powering agriculture: Present status, future potential, and challenges of renewable energy applications. Renewable Energy 188:731-749. http://doi.org/10.1016/j.renene.2022.02.065

Regnier JE, Winters R (2013) Reducing electric power costs in small water systems. Journal - American Water Works Association 105(1): 67-72. http://doi.org/10.5942/jawwa.2013.105.0053

Ribeiro MCP, Nadal CP, Rocha Junior WF, Fragoso RMS, Lindino CA (2020) Institutional and legal framework of the brazilian energy market: Biomass as a sustainable alternative for brazilian agribusiness. Sustainability 12(4):1554. http://doi.org/10.3390/su12041554

Seraphim OJ, Siqueira JAC, Putti FF, Gabriel Filho LRA, Cremasco CP, Daltin RS (2014) Energetic exploitation from a hybrid PV-wind power micro-generation rural electrification. Energy Procedia 57(1):1475-1484. http://doi.org/10.1016/j.egypro.2014.10.092

Soofi AF, Manshadi SD, Saucedo A (2022) Farm electrification: A road-map to decarbonize the agriculture sector. The Electricity Journal 35(2):107076. http://doi.org/10.1016/j.tej.2022.107076

Wang Y, Li L (2016) Critical peak electricity pricing for sustainable manufacturing: Modeling and case studies. Applied Energy 175(1): 40-53. http://doi.org/10.1016/j.apenergy.2016.04.100