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Influences of the ambient temperature, degradation effect and usage habits over the energy consumption of domestic refrigerators in Brazil

Influências da temperatura ambiente, efeito de degradação e hábitos de uso sobre o consumo de energia de refrigeradores domésticos no Brasil

Influencias de la temperatura ambiente, efecto de degradación y hábitos de uso sobre el consumo de energía de refrigeradores domésticos en Brasil

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Rafael Balbino Cardoso
ORCID: https://orcid.org/0000-0003-4239-3108
Federal University of Itajubá, Brazil
E-mail: cardosorb@unifei.edu.br

Abstract
Considering the relevance of the consumption of domestic refrigerators in the Brazilian residential sector, representing about 30% of the sectorial consumption, studies of factors that influence this consumption, such as ambient temperature, age of equipment and usage habits, are of great importance to a greater understanding of these effects and, thus, to promote better energy strategies for the country. In this sense, the present study evaluates the impacts of ambient temperature, age of the equipment and habits of use in the consumption of domestic refrigerators, based on theoretical models and laboratory tests. The laboratories assays, adhering to theoretical models, showed that the environment temperature can influence the consumption of refrigerators up to 50% less (taking into account the south region temperature), when comparing to the value that are labeled by PBE/INMETRO. When the usage habits are assayed, it was verified that the consumption of the refrigerator could be increased in up to 53%, depending the frequency of door opening.
Keywords: Consumption; Energy efficiency; Refrigerators; Usage habits.

Resumo
Considerando a relevância do consumo de geladeiras domésticas no setor residencial brasileiro, representando cerca de 30% do consumo setorial, estudos de fatores que influenciam esse consumo, como temperatura ambiente, idade dos equipamentos e hábitos de uso, são de grande importância para uma maior compreensão desses efeitos e, assim, promover melhores estratégias energéticas para o país. Nesse sentido, o presente estudo avalia os impactos da temperatura ambiente, idade dos equipamentos e hábitos de uso no consumo de refrigeradores domésticos, com base em modelos teóricos e testes laboratoriais. Os ensaios laboratoriais, aderindo a modelos teóricos, mostraram que a temperatura ambiente pode influenciar o consumo dos refrigeradores em até 50% menos (levando em consideração a temperatura da região sul), quando comparado ao valor que é rotulado pelo PBE/INMETRO. Quando analisados os hábitos de uso, verificou-se que o consumo da geladeira pode ser aumentado em até 53%, dependendo da frequência de abertura da porta.
Palavras-chave: Consumo; Eficiência energética; Refrigeradores; Hábitos de uso.

Resumen
Considerando la relevancia del consumo de refrigeradores domésticos en el sector residencial brasileño, que representa cerca del 30% del consumo sectorial, los estudios de los factores que influyen en ese consumo, como la temperatura ambiente, la antigüedad de los equipos y los hábitos de uso, son de gran importancia para una una mayor comprensión de estos efectos y, con ello, promover mejores estrategias energéticas para el país. En ese sentido, el presente estudio evalúa los impactos de la temperatura ambiente, la antigüedad de los equipos y los hábitos de uso en el consumo de refrigeradores domésticos, a partir de modelos teóricos y pruebas de laboratorio. Los ensayos de laboratorio, apegados a modelos teóricos, demostraron que la temperatura ambiente puede influir en el consumo de los frigoríficos hasta en un 50% menos (considerando la temperatura de la región sur), al comparar con el valor que marca el PBE/INMETRO. Al ensayar los hábitos de uso, se verificó que el consumo de la heladera puede incrementarse hasta en un 53%, dependiendo de la frecuencia de apertura de la puerta.
Palabras clave: Consumo; Eficiencia energética; Refrigeradores; Hábitos de uso.

1. Introduction

Due to the fact that the domestic refrigerators are mainly used for food and beverage preservation, they are the major consumers of electric energy in the Brazilian residential sector. Some studies indicate that the refrigerators are responsible for 28 % to 30% of all electricity used in Brazilian households (CEPEL, 2022 and CEMIG, 2022).

In order to estimate the energy consumption of domestic refrigerators, it is necessary the awareness of two fundamental parameters, the number of appliances installed in the residential sector and the unit consumption. In contemplation of precisely knowing the unit consumption, it is unavoidable the knowledge of some factors that influence this consumption, such as (Clasp, 2007); (Nogueira, et. al., 2015):

- ✓ The Climate where the refrigerators are installed, mainly as a consequence of the region temperature impacts over the performance coefficient (Cardoso, 2009 and Cardoso, 2011); (Kavousian, et. al., 2013); (Worrel, 2009);
- ✓ The degradation effect over the equipment's life cycle, considering that, over the years, the equipment loses performance, and, consequently the consumption of electricity becomes higher (Cardoso, 2015);
- ✓ Voltage grid variation that supplies the equipment (in other words, energy quality), because the higher variation higher will be the losses (Carmeis & Jannuzzi 2001); (WEC, 2010);
- ✓ Inappropriate combination between the management of the expansion valve and the cooling load of the refrigerator (Boeng & Melo, 2014);
- ✓ Usage habits effects in the residential sector, such as the frequency of door opening, thermostat adjustment, loading, etc (Santos, 2007); (Elliot at. al., 1997).

The Brazilian Labeling Program - PBE/INMETRO labels the refrigerators classifying them per their efficiency, classes that vary from A (more efficient) to E (less efficient) (Fonseca et. al., 2018). In order to attribute the labels from PBE/INMETRO, the refrigerators are assayed in adiabatic chambers at a temperature of 32 degrees Celsius, in accordance with the conditions established by the ISO Standard 7371/1995, incorporated into the NBR ISO/IEC 17025/2001. Because of the Brazil`s territorial dimension, with different temperature conditions, different age of the equipment installed in the residences and different profile of usage habits, the consumption of the refrigerators are influenced by these parameters and their real consumption are different from the ones established by the assay conditions (Capaz and Nogueira, 2015); (Eletrobrás,2007).

In this context, this study analyses the effect of ambient temperature, age of equipment and usage habits over the consumption of the refrigerators in the Brazilian residential sector, through theory, taking into account the energy efficiency label (PBE/INMETRO) and, laboratory experiments, with a 2 doors refrigerator model.

2. Methodology: Influences of Ambient temperature, Age and Usage Habits Over the Consumption

This chapter presents the theoretical equation, as well as the laboratory procedures, for the estimates of the impact of ambient temperature, performance degradation and usage habits over the consumption of the domestic refrigerators. Quantitative methods were used to develop the methodology of this paper.

2.1 Theoretical Equation

In the interest of estimating the consumption of the representative model, it was necessary a formulation of a model equation, which uses the unit consumption per liter per month of each labeled class (A, B, C, D or E) by PBE/INMETRO.

First, the unit consumption per liter per month was estimated for each equipment, considering their total volume, after, an average consumption for each class was calculated and, then, applied to the volume of the representative model of the study. Gathering all this information, the Equation 1 was developed.

$$Cstandard = Ci,unit \times Vmodel \times 12 \quad (1)$$

Where:

Cstantard – Estimated annual consumption for the model (kWh/year), assayed conditions;

Ci,unit – Unit consumption of a determined class (i) in kWh per liter per month;

Vmodel – Representative model volume, in liters.

To estimate the effects of the ambient temperature, in isolation, it was elaborated an equation model. Utilizing the Equation 1 and the theoretical equation of temperature correction, it was developed the Equation 2, shown below.

$$Cadjusted = Ci,unit \times Vmodel \times 12 \times (T-5)/27 \quad (2)$$

Where:

Cadjusted – Adjusted consumption considering the ambient temperature, in kWh/year;

Ci,unit – Unit consumption of a determined class (i) in kWh per liter per month;

Vmodel – Representative model volume, in liters;

T – Ambient temperature, in Celsius.

In pursuance of estimating the combined effect of the ambient temperature and the degradation effect, it was applied the Equation 2 with a degradation coefficient (which considers the age and the efficiency losses of the equipment) and, then, elaborated the Equation 3.

$$Cr = Cadjusted \times DCi \quad (3)$$

Where:

Cr – Real consumption (ambient temperature and degradation effects applied), in kWh/year;

Cadjusted – Adjusted consumption considering the ambient temperature, in kWh/year;

DCi – Degradation coefficient for the age “i”.

2.2 Laboratory Procedures

In order to perform the assay it was used a two-door refrigerator made by MABE/BOSCH (model KDV47A00BR/25), an air conditioner type Split made by HITACHI, model RAA24A, an energy consumption analyzer (Fluke 437-II) and a thermometer (EXTECH 45160 3-in-1 Humidity, Temperature and Airflow meter), in a laboratory, with environment control, from the Federal University of Itajubá – UNIFEI. The Figure 1 presents the two-door refrigerator and the air conditioner used in the assay, and, the Figure 2 shows the Fluke 437-II used to measure the energy consumption.

Figure 1 - Two-door refrigerator of 416 liters of total volume made by MABE/BOSCH (127V and 222 W) assayed and air conditioner.

Source: From Author.

Figure 2 - Fluke 437 Series II Power Quality and Energy Analyzer.

Source: From Author.

It was developed two experiments, described below:

Experiment 01: The first experiment (in order to verify the temperature impacts) was developed in one day, on July 12th 2017. The laboratory assays had the main objective of verifying the behavior of the energy consumption, taking into account the influences of the ambient temperature, measured at 16°C, 20°C, 20.3°C e 20.7°C. In this experiment, the refrigerator was always with the doors closed.

Experiment 02: The second experiment has the main objective of verifying the combined effect of temperature and usage habits. To perform these experiments, it was selected 2 temperatures, 15.5 °C and 20.7 °C. Relating to the usage habits, it was developed 2 different experiments of door opening (both doors, from the refrigerators and freezer at the same time), one

considering only one cycle of door opening, and, the other one, two cycles of door opening. For each cycle of door opening, it was developed 4 rounds of door opening (30 seconds of duration for each round). The 4 rounds were made in an interval of 2 hours within each other. The experiment that considered only one cycle of door opening was developed in a temperature of 15.5 °C while the other one, with the double of cycle, was performed in a temperature of 20.7 °C.

3. Theoretical Results of Energy Consumption and Energy Savings

This chapter presents the results of the energy consumption and energy savings potential over the theoretical models, considering the effects of the ambient temperature as well as the degradation effects, taking into account the energy efficiency label.

Since this study analyzes a large number of refrigerators, it was defined a representative model, using the energy consumption table (for refrigerators) provided by PBE/INMETRO, available on the INMETRO`s website. It was analyzed 448 refrigerators (both operation system, 127 V and 220 V) with total volumes varying within 200 and 600 liters, and, then, it was developed a representative model of an adjusted volume of 350 liters (representing the majority number of refrigerators in the Brazilian market). The Table 1, shown below, presents the unit consumption of each class labeled by PBE/INMETRO.

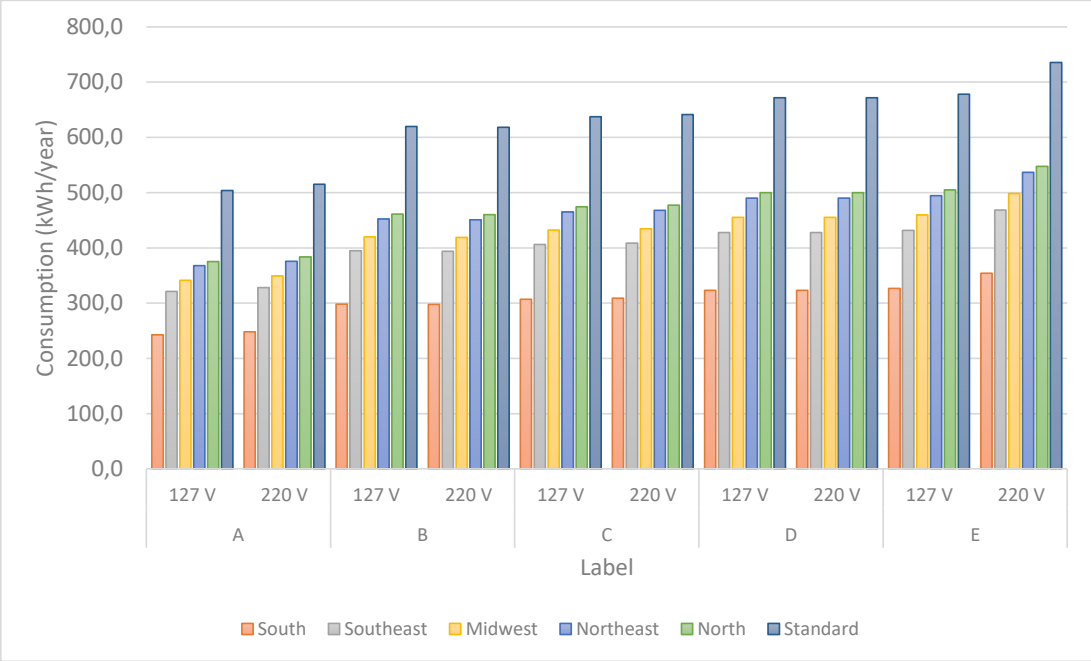
Table 1 - Representative Model Energy Consumption of 350 liters.

Representative Model Sort by Classes					
Class Parameter	A	B	C	D	E
kWh/month/liter (127V)	0.12010	0.14752	0.15174	0.15989	0.16142
kWh/month/liter (220V)	0.12267	0.14716	0.15271	0.15989	0.17512
127 V (kWh/month)	42.0	51.6	53.1	56.0	56.5
220 V (kWh/month)	42.9	51.5	53.4	56.0	61.3

Source: From Author.

By using the Equation 2 and the average regional annual temperature of each geographic Brazilian region, it was possible to calculate the theoretical consumption from each region, presented in the Figure 3. The temperatures used for these calculi were taken from Cardoso et al. (2009), which, for the regions North, Northeast, Middle East, Southeast and South, represent, respectively, 25.1 °C, 24.7 °C, 23.3 °C, 22.2 °C e 18.0 °C.

Figure 3 - Comparison of the consumption of the equivalent 350 liters refrigerator, considering the Norm and the region temperature.



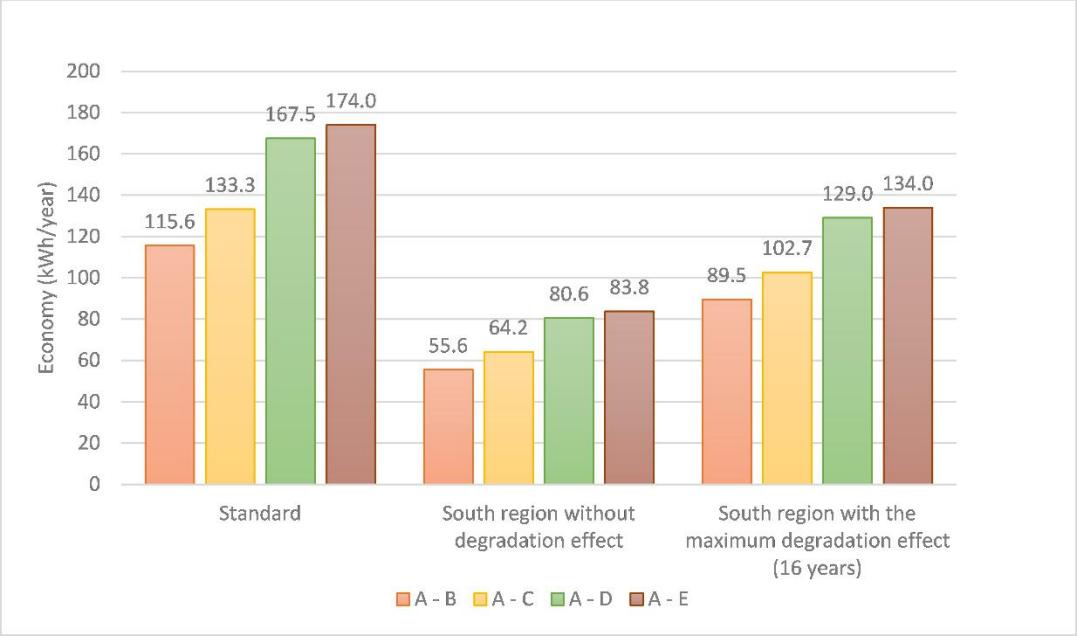
Source: From Author.

The Figure 3 shows that, taking into account the class "A" refrigerators, it is noticeable that in the South region, due to the ambient temperature influence, it is estimate a real consumption about 50 % less than the Norm, showing that the ambient temperature has a significant impact over the consumption.

If the performance degradation effects were taken into account, the appliances until 5 years old would not suffer significant effects due to the degradation effects. When it is considered 5 to 10-year-old refrigerators, their consumption can be increased about 20 % compared to a new equipment, and, 10 to 16-year-old refrigerators, about 60 % above the labeled consumption (Cardoso, 2011).

The effects of ambient temperature and performance degradation can affect the estimates of the energy savings in a specific program, as an example the PBE/INMETRO. The Figure 4 shows the difference of the energy savings by purchasing an equipment more efficient (class "A"), considering these effects.

Figure 4 - Energy saving potential of the representative model, operating at a voltage of 127 V, and the conditions previously commented (kWh/year).



Source: From Author.

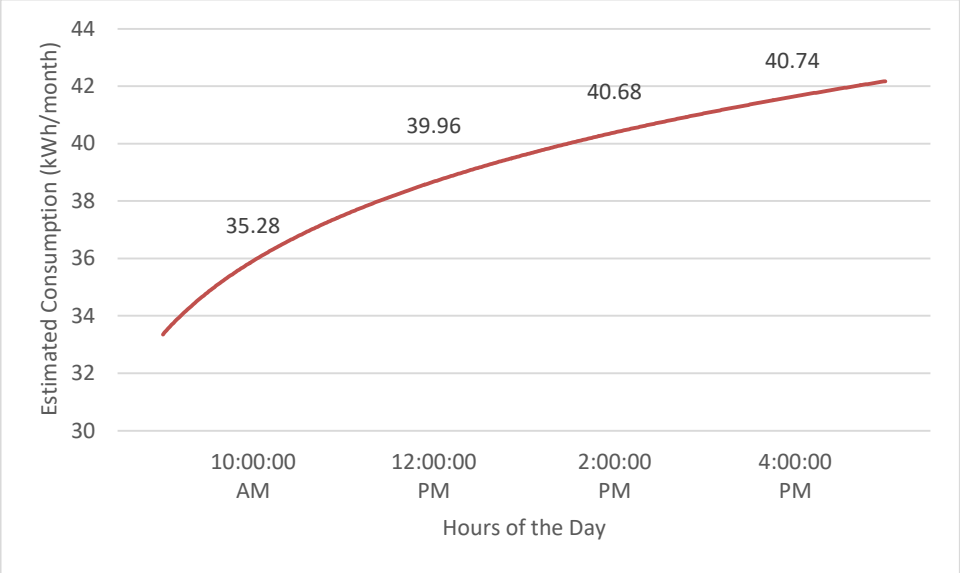
It is possible to Identify, on the Figure 4, the energy savings potential for the 3 presented situations. Taking into account the difference between the class "A" and "E", under standard conditions, it is observed an economy of 174 kWh/year. When analyzing the situation of a new equipment, operating in the South region, it is verified that the economy decreases to 83.8 kWh/year. Applying the maximum degradation effect (16 years of operating), it is observed an economy of 134 kWh/year.

4. Laboratory Results Considering The Ambient Temperature and the Usage Habits over the Consumption

a) Results referring to the ambient temperature influences

The first experiment performed was the short duration assay, which analyzes only the ambient temperature effect on the consumption of the refrigerator. Using the data collected, it was developed a graphic to better demonstrate the behavior of the consumption throughout the day, shown in Figure 5. The hours of the day, shown in the graphic, represent the changing of the ambient regulated temperature, beginning with a regulated temperature of 16 °C at 10 am, then the hours 12 pm, 2 pm, and 4 pm, represents, respectively, 20 °C, 25 °C and 32 °C.

Figure 5 - Verified consumption of the refrigerator throughout the day (temperature impacts).



Source: From Author.

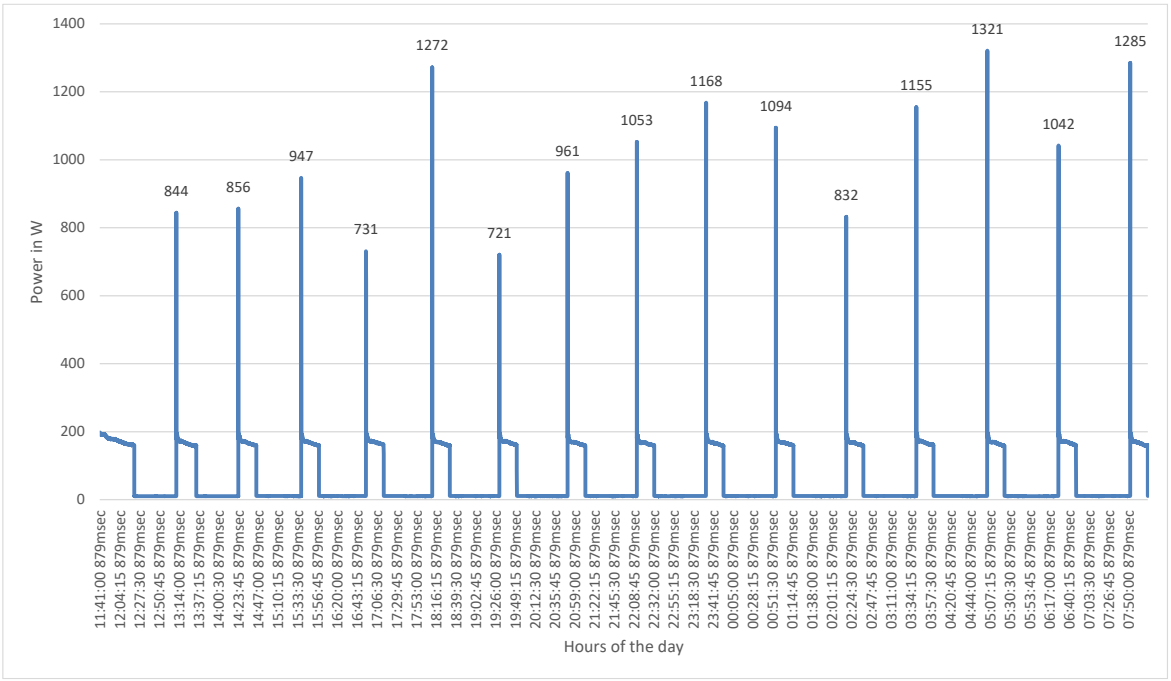
The Figure 5 shows that, throughout the day, the regulated temperature was gradually increased, and, consequently, the consumption increased. When the temperature was regulated at 20 °C, the verified consumption was 39.96 kWh/month, 13.30% higher comparing the one at a temperature of 16 °C.

b) Results referring to the usage habits influences

It was elaborated, in one of the assays, an ambient with a measured temperature at 15.5 °C and one cycle of door opening. After this assay, it was developed another test at an ambient temperature, measured in laboratory, of 20.7 °C and two cycles of door opening.

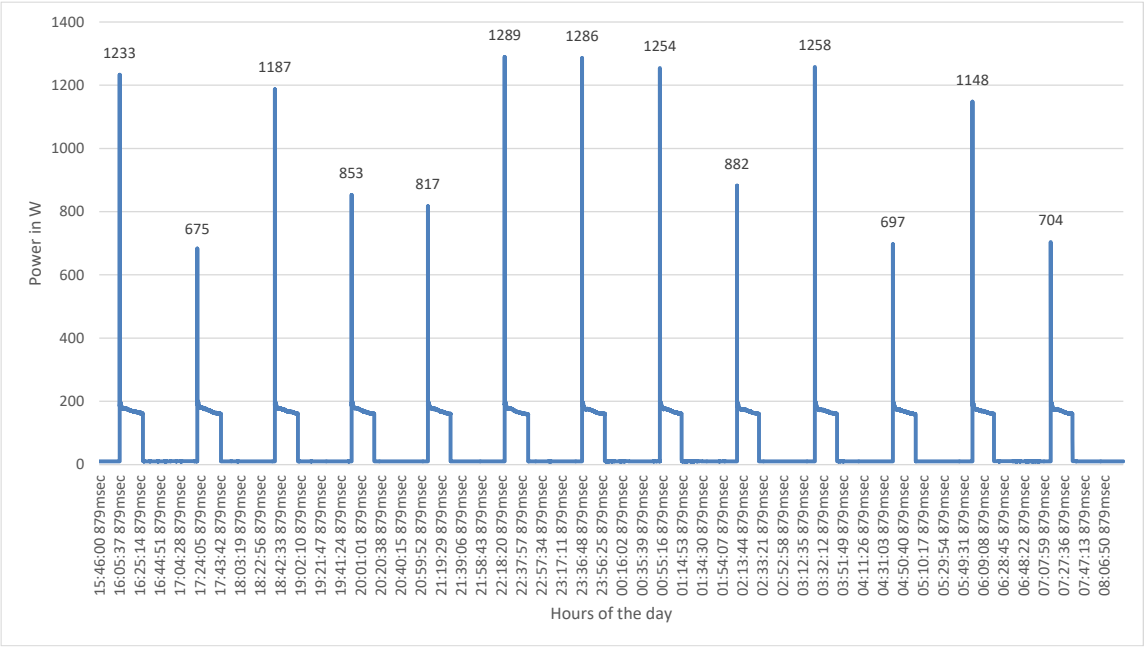
The Figures 6 and 7 present the behavior of the active power of the assayed refrigerator with the cycles of door opening at 15.5 °C and 20.7 °C, as described previously.

Figure 6 - Behavior of the active power of the assayed refrigerator, with one cyle of door opening, at 15.5 °C.



Source: From Author.

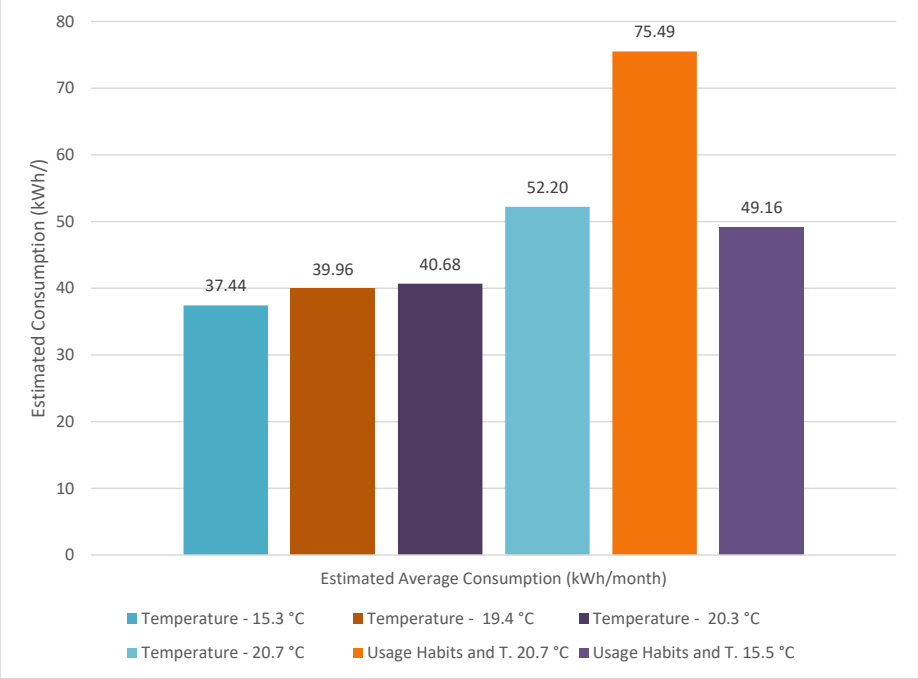
Figure 7 - Behavior of the active power of the assayed refrigerator, with two cycles of door opening, at 20.7 °C



Source: From Author.

The Figures 6 and 7 show that the higher is the frequency of door opening, the higher is the peak power throughout the day. They also show that as the time of operation gets higher, the difference of the consumption gets higher too. This increasing on the consumption can reach more than 50 %, comparing to the using with the doors closed, as presented in the Figure 8.

Figure 8 - Average consumption of the four short assays in comparison to the two usage habits and temperature effects.



Source: From Author.

Overall, when the refrigerator was assessed in a temperature of 15.3 °C (measured in laboratory) it was estimated an average consumption of 37.44 kWh/month. In addition, when applying the usage habits (one cycle of door opening), at a very similar temperature (15.5 °C), it was observed an estimated temperature of 49.16 kWh/month, an increase of, approximately, 31 % due to the usage habits.

Doubling the usage habits effects, as well as regulating the temperature at 20.7 °C, the estimated consumption was 79.49 kWh/month, approximately 53% higher than the registered with the doors closed.

5. Conclusion

This study showed that the ambient temperature and the performance degradation affect, in a significant way, the energy consumption of these coolers, independently of the energy efficiency label or voltage level that they operate. The results showed that the annual energy consumption of the refrigerators that operate in the South Region could represent almost half of the energy consumption presented on the label, if considering only the ambient temperature effects.

The results of the potential energy saving of the refrigerators that are more efficient (class "A) is lower in colder regions, as an example, the South Region of Brazil. When the performance degradation effects over the lifetime are considered in the energy saving estimates, the potential energy saving can increase significantly.

Regarding the laboratory assays in this research, it was observed that the consumption of a refrigerator is significantly affect by the temperature and the usage habits (frequency of door opening). These experiments show that the ambient temperature can decrease, in some Brazilian`s regions, about 30% on the consumption of the refrigerators, number in accordance to the theoretical model.

The research showed, also by the experimental results, that the usage habits (frequency of door opening) could increase the consumption of domestic refrigerators up to 53 %, when comparing to the consumption with the doors closed.

Lastly, both temperature and usage habits are parameters that influence significantly the energy consumption of domestic refrigerators, and, must be considered in energy strategies, as in the evaluation of Energy Efficiency Programs.

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