# Bottom-up modelling of electricity end-use consumption of the residential sector in Brazil

## *Modelagem* bottom-up *do consumo por uso final de eletricidade no setor residencial no Brasil*


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## Abstract

Electricity consumption in the residential sector in Brazil has been increasing annually despite efforts to promote the energy efficiency of household appliances. One of the main goals for achieving more energy efficiency in dwellings is understanding its energy end uses. In this context, this paper presents a bottom-up model developed to analyse regional and national electricity end uses in the residential sector in Brazil based on a recent survey on Ownership of Appliances and Consumption Habits. The percentages of total electricity consumption associated with nine appliances (light bulbs, refrigerators, freezers, televisions, showers, microwaves, washing machines, fans, and air conditioners) were estimated. The values were obtained using the software EnergyPlus for air conditioners and electricity consumption equations for the other eight appliances. Results show that the proposed model gives reasonable estimates of electricity consumption, which were close to the values expected for most appliances. Regionally, the appliances for which ownership and pattern of use are influenced by the climate (electric showers, fans, and air conditioners) obtained the most significant variation in the percentage of electricity consumption.



**Keywords:** Energy modelling. Bottom-up. Residential electricity end use.



## Resumo

*O consumo de energia no setor residencial brasileiro tem aumentado significativamente, apesar dos esforços para promover a eficiência energética dos eletrodomésticos. Um dos principais objetivos para a melhoria da eficiência energética nas residências é entender seus usos finais de energia. Neste contexto, este artigo apresenta o desenvolvimento de um modelo bottom-up para analisar os usos finais de energia regionais e nacionais no setor residencial brasileiro com base na Pesquisa de Posse e Hábitos de Uso de Equipamentos Elétricos na Classe Residencial. Foram estimados os percentuais do consumo total de energia elétrica associados a nove eletrodomésticos (lâmpadas, geladeiras, freezers, televisores, chuveiros, microondas, máquinas de lavar, ventiladores e condicionadores de ar). Os valores foram obtidos por meio do software EnergyPlus para condicionadores de ar e com equações de consumo de energia elétrica para os outros oito aparelhos. Os resultados mostram que o modelo proposto fornece estimativas razoáveis de consumo de energia elétrica, próximas aos valores esperados para a maioria dos eletrodomésticos. Observou-se que a posse e utilização dos eletrodomésticos, influenciados pelo clima (chuveiros elétricos, ventiladores e condicionadores de ar), obtiveram a maior variação no percentual de consumo de energia elétrica.*



***Palavras-chave**: Modelagem energética. Bottom-up. Uso de eletricidade residencial.*



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## Introduction

Electricity is the fastest growing form of energy consumption globally, increasing from 13,156 TWh in 2000 to 23,031 TWh in 2018, in which consumption in buildings represented more than half of this value (INTERNATIONAL..., 2019). In Brazil, electricity consumption reached almost 475 TWh in 2018, of which 29% was destined for the residential sector (EMPRESA..., 2019a). The large percentage of total electricity consumption represented by residential buildings in Brazil has been an object of concern for the Brazilian government since the 1980s when it started investing in the development of energy certificates. The focus was on stimulating consumers to buy energy- efficient appliances in order to reduce household electricity consumption. Despite these efforts to promote energy efficiency, electricity consumption in the residential sector in Brazil is increasing faster than the national average. From 2006 to 2018, the residential electricity consumption increased by 60.4%, while the total electricity consumption in the country increased by 33.3% (EMPRESA..., 2019a, 2019b). The residential sector is heterogeneous, with many end uses. Their consumption may vary across this vast country with different climates and geographical regions in different stages of development. In this context, the development of up-to-date energy models that can provide data on electricity end uses in the Brazilian residential sector is essential to identify appliances with the highest energy consumption on a national and regional basis and help implement more effective energy efficiency measures.

In Brazil, electricity consumption associated with end uses in the residential sector is generally estimated using electricity consumption equations that use the average electricity consumption to estimate the electricity consumption of the appliances or considering the power of the appliances and their time of use. The consumption of energy end uses in the residential sector was analysed by Achão and Schaeffer (2009) in 11 metropolitan regions in Brazil: Belém, Fortaleza, Recife, Salvador, Curitiba, Porto Alegre, Belho Horizonte, Rio de Janeiro, São Paulo, Brasília and Goiânia. Equations were adopted to determine the consumption of equipment as food consumption and stoves, shower, food preservation, and lighting. The results showed that in 6 of the 11 metropolitan regions (Fortaleza, Salvador, Curitiba, Rio de Janeiro, Brasília, and Goiânia) the consumption estimate was close to the consumption measured by the energy concessionaires. Ghisi, Gosch and Lamberts (2007) estimated the electricity consumption associated with ten appliances: light bulbs, refrigerators, freezers, televisions, electric showers, washing machines, microwave ovens, irons, sound systems, and air conditioners. The estimates were based on electricity consumption equations that consider pre-defined values for average electricity consumption per appliance (PROGRAMA..., 2006) and data on the number of appliances (ELETROBRAS, 2019). The Brazilian survey on Ownership of Appliances and Consumption Habits is conducted every 10 years, detailing information about residential buildings in Brazil and their associated appliances and patterns of use since 1988. Fedrigo *et al.* (2009) estimated the electricity consumption of fifteen appliances: refrigerators, freezers, air conditioners, electric showers, televisions, light bulbs, sound systems, computers, irons, dishwashers, washing machines, clothes dryers, microwave ovens, electric stoves, and electric faucets. The estimates were also performed based on the appliances in the survey on the Ownership of Appliances and Consumption Habits database, but considering a later version, researched between 2004 and 2006 (PROGRAMA..., 2007). The developed electricity consumption equation estimates the consumption based on multiplying the time of use of each appliance by its pre-defined power value. The Brazilian residential electricity consumption between 2000 and 2018 was analysed by Abrahão and Souza (2021). The authors investigate the Brazilian residential electricity consumption growth on a regional level by applying the Index Decomposition Analysis – IDA and Logarithmic Mean Divisia Index I – LMDI-I. Results showed that residential electricity consumption in Brazil varies with population age and positively with the economically active phase of life, up to the age of 59, mainly in the Southeast and South regions.

The techniques used to develop these energy models are grouped into two general categories: top-down and bottom-up (SWAN; URGUSAL, 2009). The models developed with the top-down approach work with aggregated data on energy consumption, without distinguishing between individual end uses, and, through regression techniques, they estimate the effects of ongoing long-term changes, such as climatic conditions, energy prices, and gross domestic product, on energy consumption associated with buildings (ZHANG, 2004; SUMMERFIELD; LOWE; ORESZCZYN, 2010). In contrast, the bottom-up approach works on a disaggregated level. It makes use of information on individual dwellings and electricity end uses, generally obtained from census data or surveys on the building stock (MATA; KALAGASIDIS; JOHNSON, 2014), as inputs for a model used to estimate energy consumption associated with residential buildings. Since bottom-up models frequently consider a large number of dwellings, the models developed with this approach tend to aggregate dwellings according to their common characteristics, generating representative buildings, which are used to estimate the electricity consumption in the broader residential sector (STREICHER *et al.*, 2019). Energy models based on the top-down method are easier to develop since they consider the residential sector as a whole, with no need to develop reference buildings and use aggregated data that are easy to find in the literature. However, the lack of detailed information on end uses hinders the ability of the top-down models to identify critical areas where reductions in energy consumption need to be made (BALLARINI; CORGNATI; CORRADO, 2014; WANG *et al.*, 2018; UIDHIR *et al.*, 2019; TANIGUCHI-MATSUOKA *et al.*, 2020).

Bottom-up models usually require a large amount of data (KAVGIC *et al.*, 2010) to provide valuable results. Due to technological advances in home appliances and changes in their trends over time, it is essential to have access to an up-to-date database containing the information needed to perform the bottom-up analysis.

In 2019, an updated survey on Ownership of Appliances and Consumption Habits was published, providing information on 18,775 Brazilian dwellings (ELETROBRAS, 2019). Based on this updated publication delivered in 2019, the main aim of this paper is to present a bottom-up model to analyse regional and national electricity end uses in the residential sector in Brazil based on a recent survey on Ownership of Appliances and Consumption Habits. Nine appliances were considered in this study: light bulbs, refrigerators, freezers, televisions, showers, microwave ovens, washing machines, electric fans, and air conditioners. The results were compared with those reported by Ghisi, Gosch and Lamberts (2007) and Fedrigo *et al.* (2009), which were based on two previous research studies conducted by the survey on Ownership of Appliances and Consumption Habits based on 1997-1998 and 2004-2006, respectively, in order to give an overview on the electricity consumption estimates derived for the Brazilian residential sector.

# Method

## Brazilian survey on ownership of appliances and consumption habits

The Brazilian survey on Ownership of Appliances and Consumption Habits (PPH) provides a profile on the ownership and pattern of use of electrical equipment in the residential, commercial and industrial sectors every 10 years in Brazil (ELETROBRAS, 2019). The first survey was conducted in 1988, the second in 1997-1998 and the third in 2004-2006. The fourth and latest version was published in 2019 and only included data from the residential sector. For the 2019 survey, information was collected for 6,100 dwellings in the Northeast region, 4,375 dwellings in the North region, 3,925 dwellings in the Southeast region, 2,500 dwellings in the Central-West region, 1,875 dwellings in the South region, totalising 18,775 dwellings.

A wide variety of information was obtained regarding the inhabitants, their dwellings and appliances, and their use patterns. Regarding appliances, the data collected can be divided into three groups based on the information obtained. The first relates to light bulbs. In this case, data on the number of light bulbs, their technology (incandescent, fluorescent, light emitting diodes - LED, dichroic), and hours of daily use were collected for each room. Information on their power was gathered for incandescent, fluorescent, and light emitting diodes (LED) light bulbs. The second group covers refrigerators, freezers, televisions, electric showers, microwaves, washing machines, and air conditioners. A more detailed set of data was collected, including the number of appliances and their technology, physical characteristics, frequency of use, and hours of daily use. The third group consists of 46 appliances, including electric fans, notebooks, and blenders. For this group, the data collected was the number of appliances, frequency, and hours of use. The information collected by Brazilian surveys on Ownership of Appliances and Consumption Habits is publicly available and can be accessed in Eletrobras (ELETROBRAS, 2019).

Brazil is the largest and most populous country in South America, with 212 million people and 71 million dwellings (INSTITUTO…, 2019a, 2019b). The country is divided into five geographical regions: North, Northeast, Central-West, Southeast, and South. The South, Southeast, and Central-West regions, the richest in the country, with a mean household monthly income per person above 1.4 minimum wages (INSTITUTO…, 2019c), have the highest values for mean annual electricity consumption per dwelling (above 2,000 kWh each). On the other hand, the poorest regions (North and Northeast), with a mean household monthly income per person below 0.9 minimum wages, have a mean annual electricity consumption below 1,800 kWh.

## Bottom-up approach

The electricity end uses were estimated following the four steps shown in Figure 1. In Step 1, an R script was created with the software RStudio (RSTUDIO, 2019) (R is a free software environment for statistical computing and graphics). This script is responsible for importing The Brazilian survey on Ownership of Appliances and Consumption Habits (PPH) database and selecting the information needed to estimate the regional and national electricity consumption associated with light bulbs, refrigerators, freezers, televisions, showers, microwave ovens, washing machines, electric fans, and air conditioners. These appliances accounted for a significant percentage of the electricity consumption in the residential sector and were also reported by Ghisi, Gosch and Lamberts (2007) and Fedrigo *et al.* (2009). In Step 2, the information collected by the script was used to estimate the electricity consumption of the nine appliances mentioned above for all dwellings included in the PPH database. The electricity consumption was performed with the software EnergyPlus, version 9.1, for air conditioners and with electricity consumption equations for the other appliances. In Step 3, the electricity consumptions associated with each appliance were estimated, aiming to reflect the consumption of all dwellings in each state. In Step 4, the estimated consumptions of all dwellings were aggregated and divided by actual residential electricity consumption data found in the literature to obtain regional and national percentages of electricity consumption for each end use. The estimated percentages were then compared with the results reported by Ghisi, Gosch and Lamberts (2007) and Fedrigo *et al.* (2009). This comparison aimed to provide an overview of the electricity consumption estimates obtained for the Brazilian residential sector.

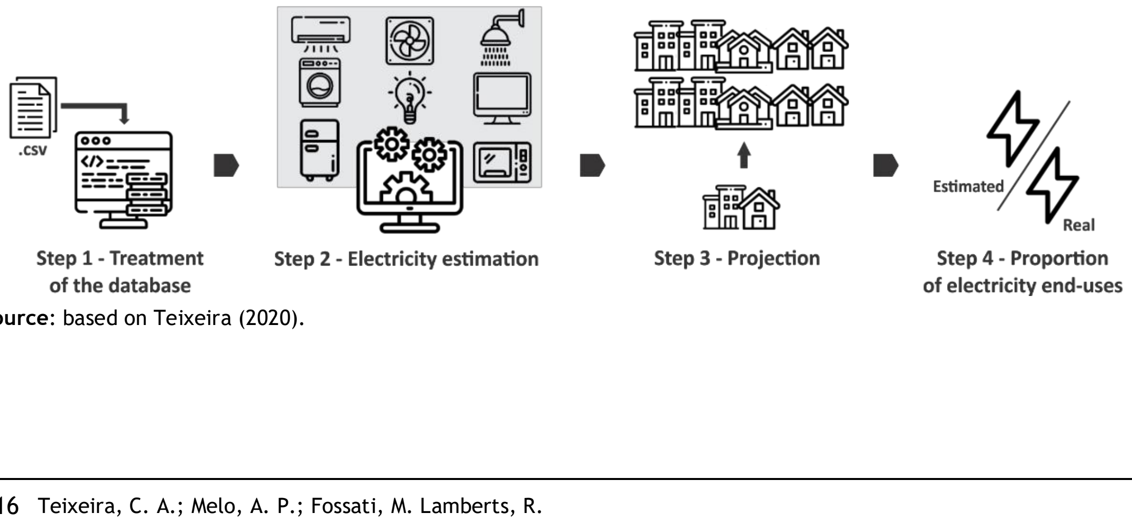
### Step 1: the database

In Step 1, an R script was created with the software RStudio (2019), responsible for importing the latest survey database and selecting the information needed to estimate the regional and national electricity consumption associated with light bulbs, refrigerators, freezers, televisions, showers, microwave ovens, washing machines, electric fans, and air conditioners. Regarding the power of the appliances, the survey only provides data for light bulbs and electric showers. However, information on the technology and the physical characteristics of refrigerators, freezers, televisions, microwave ovens, and washing machines are categorised similarly to the appliances certified by the Brazilian Labeling Program (PBE). Thus, mean values can be obtained for the power or specific electricity consumption for the appliances included in the PBE database (INSTITUTO…, 2019) along with the technology and physical characteristics. In the case of electric fans, as the survey did not collect information on the technology and physical characteristics, the power was estimated based on the mean power value for all fans included in the PBE database.

### Step 2: electricity consumption estimation

In Step 2, the information collected by the script was used to estimate the electricity consumption of the nine appliances mentioned above for all dwellings included in the survey database. The electricity consumption was performed with the software EnergyPlus, version 9.1 (ENERGYPLUS, 2019), for air conditioners and electricity consumption equations for the other appliances. The building energy simulation allows a closer analysis regarding the energy consumption of air conditioning in dwellings, as it allows local climate weather data.

Figure 1 – **Flow chart of procedure applied in this study**




**Source**: based on Teixeira (2020).

The annual electricity consumption of light bulbs was estimated for each room, based on Equation 1:

$$C_{l,room} = \sum_{t,w} Prop_{t,w}\ x\ P_{t,w}\ x\ T\ x\ 365 \qquad \text{Eq. 1}$$

Where:

$C_{l,room}$ is the annual electricity consumption of light bulbs for each room (kWh);

$Prop_{t,w}$ is the proportion of light bulbs of the same technology and power range;

$P_{t,w}$ is the representative power (kW);

*T* is the hours of daily use of all light bulbs in the same type of room (hours);

*t* is the technology of the light bulb (incandescent, fluorescent and LED); and

*w* is the power range.

The electricity consumption values for all rooms ($C_{l,room}$) were then summed to estimate the total electricity consumption for all light bulbs.

The values for the annual electricity consumption of refrigerators and freezers were estimated using Equation 2:

$$C_{ref,free} = \sum_{t,v} N_{t,v}\ x\ C_{t,v}\ x\ 12 \qquad \text{Eq. 2}$$

Where:

$C_{ref,fre}$ is the annual electricity consumption of refrigerators or freezers *(kWh)*;

$N_{t,v}$ is the number of appliances of the same technology and volume;

$C_{t,v}$ is the representative monthly electricity consumption (kWh/month), based on the PBE database; and

*t* is the technology; and *v* is the volume.

The climate differences of the five geographic regions in Brazil were not considered in Equation 2. Therefore, the electricity consumptions associated with end uses were also estimated considering the equation developed by Cardoso, Nogueira and Haddad (2010), who adapted the electricity consumption of appliances included in the PBE database, or, in this case, their representative monthly electricity consumption ($C_{t,v}$), according to the climate of the region, as shown in Equation 3.

$$C'_{tv} = C_{t,v}\ x\ \frac{T_{reg}-5}{27} \qquad \text{Eq. 3}$$

Where:

$C'_{t,v}$ is the adapted monthly electricity consumption (kWh/month);

$T_{reg}$ is the annual average temperature of the region defined in Cardoso *et al*. (2010);

$C_{t,v}$ is the representative monthly electricity consumption (kWh/month) and based on the PBE database;

*t* is the technology;

*v* is the volume; and

*reg* is the region.

The $C'_{t,v}$ values for each type and volume of refrigerator and freezer were then used in Equation 2 to obtain the annual electricity consumption results according to the climate of the regions.

The annual electricity consumption of televisions was estimated based on Equation 4:

$$C_{tv} = \sum_{t,s} Prop_{t,s}\ x\ P_{t,s}\ x\ T\ x\ 12 \qquad \text{Eq. 4}$$

Where:

$C_{tv}$ is the annual electricity consumption of televisions (kWh);

$Prop_{t,s}$ is the proportion of televisions of the same technology and size;

$P_{t,s}$ is the representative power (kW) and based on the PBE database;

*T* is the hours of monthly use of all televisions (hours);

*t* is the technology; and

*s* is the screen size.

The annual electricity consumption of microwaves was estimated based on Equation 5:

$$C_{mic} = \sum_{v} Prop_{v}\ x\ P_{v}\ x\ T\ x\ 12 \quad \text{Eq. 5}$$

Where:

$C_{mic}$ is the annual electricity consumption of microwave ovens (kWh);

$Prop_v$ is the proportion of microwave ovens of the same volume;

$P_v$ is the representative power (kW) and based on the PBE database;

*T* is the number of hours of monthly use for all microwave ovens (hours); and

*v* is the volume.

The annual electricity consumption of washing machines was estimated based on Equation 6:

$$C_{wm} = \sum_{t,cap} Prop_{t,cap}\ x\ C_{t,cap}\ x\ n\ x\ 12 \quad \text{Eq. 6}$$

Where:

$C_{wm}$ is the annual electricity consumption of washing machines (kWh);

$Prop_{t,cap}$ is the proportion of washing machines of the same technology and capacity;

$C_{t,cap}$ is the representative electricity consumption per cycle *(kWh/cycle)* and based on the PBE database;

*n* is the monthly number of cycles of all washing machines;

*t* is the technology; and

*cap* is the capacity.

For electric showers, the Brazilian survey on Ownership of Appliances and Consumption Habits (ELETROBRAS, 2019) provides information on the months that each shower is used with maximum or intermediate temperatures or no increase in water temperature. Thus, firstly, the monthly electricity consumption was calculated considering all showers with maximum or intermediate water temperature, as shown in Equation 7:

$$C_{sh} = \sum_{p,temp} Prop_{p}\ x\ P_{p,temp}\ x\ T\ x\ 30 \quad \text{Eq. 7}$$

Where:

$C_{sh}$ is the monthly electricity consumption of showers (kWh);

$Prop_p$ is the proportion of showers with the same range of power;

$P_{p,temp}$ is the representative power according to the range of power and water temperature (kWh) and based on mean values estimated using the PBE database;

*T* is the hours of monthly use of all showers *(hours)*;

*p* is the range of power; and

*temp* is the water temperature (maximum or intermediate).

The annual electricity consumption of electric showers was then calculated based on Equation 8:

$$C_{sh\_year} = \sum_{m} Proph_{m}\ x\ C_{h}\ x\ Propi_{m}\ x\ C_{i} \quad \text{Eq. 8}$$

Where:

$C_{sh\_year}$ is the annual electricity consumption of electric showers (kWh);

$Proph_m$ is the proportion of showers used with maximum water temperature;

$C_h$ is the respective monthly electricity consumption (kWh) and based on Equation 7;

*Prophi* is the proportion of showers used with intermediate water temperature;

$C_i$ is the respective monthly electricity consumption (kWh) and based on Equation 7; and

*m* is the month.

The annual electricity consumption of electric fans was estimated based on Equation 9:

$C_{vent} = P \, x \, T \, x \, \mathrm{N}$ Eq. 9

Where:

$C_{vent}$ is the annual electricity consumption of electric fans (kWh);

$P$ is the power, fixed at 0.0748 kW and based on a mean value estimated using the INMETRO database (INSTITUTO…, 2019);

$T$ is the hours of monthly use of all fans (hours); and

$N$ is the number of months in which the fan is used.

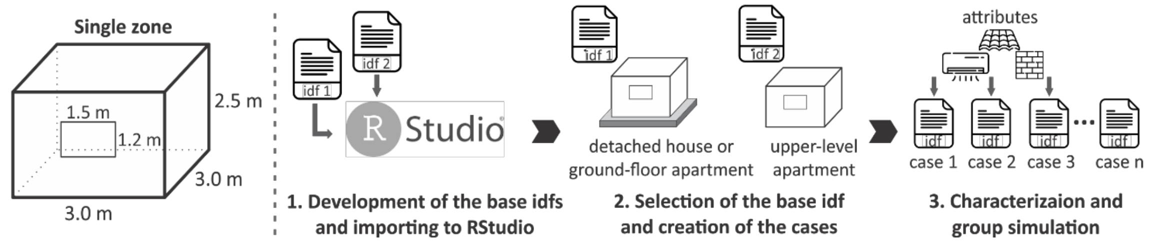
The $N$ value is seasonal use (set at four months) in the South and Southeast regions and annual use for the Central-West, Northeast, and North regions.

The annual electricity consumption for heating and cooling was estimated with the building energy simulation program EnergyPlus, version 9.1. The process of generating the simulation models is detailed in Figure 2. The total energy consumption for heating, cooling, and fan were converted to kWh to estimate the annual consumption for artificial conditioning.

The modelling process starts by developing two idf (Input Data File) files (input files to EnergyPlus program) created to receive information on air conditioners and dwellings through an R Script developed for this purpose. In both idf files, a single zone was modelled to represent the air conditioner room since the survey did not provide sufficient information to model the entire dwelling. As most air conditioners in the survey database operate throughout the night, it was considered a representative room (single zone) in dwellings in Brazil with a floor area of 9.0 m$^2$ (3 m x 3 m x 2.5 m). The single zone was defined based on research developed by Teixeira *et al*. (2015), which observed a significant percentage of the room area in Brazilian dwellings close to 9 m$^2$.

The single zone comprises two exterior walls, one single glazed window, and two interior walls set as adiabatic. The window has a solar factor of 0.87 and transmittance of 5.7 W/m$^2$K. The information taken from the Brazilian survey consists of the type of walls and roofs, the colour of the walls, and the window's orientation. The single zone was simulated considering all the information presented in Tables 1 and 2, changing one parameter by time (parametric simulation). The information on the materials used to model roofs and walls was adopted based on Weber (2018).

Figure 2 – **Modelling of the cases**




**Source**: based on Teixeira (2020).

Table 1 – **Characteristics of roofs and walls**

| Surface | Materials | Thermal transmittance | Thermal capacity |
|---|---|---|---|
| Roof | Concrete slab | 3.73 W/m$^2$K | 220 kJ/m$^2$K |
| | Fibre cement with attic and wood ceiling | 2.02 W/m$^2$K | 21 kJ/m$^2$K |
| | Ceramic tile with attic and wood ceiling | 2.02 W/m$^2$K | 26 kJ/m$^2$K |
| Wall | Concrete wall | 4.40 W/m$^2$K | 220 kJ/m$^2$K |
| | Clay bricks with internal and external plastering | 2.46 W/m$^2$K | 150 kJ/m$^2$K |
| | Clay bricks without plastering | 2.99 W/m$^2$K | 42 kJ/m$^2$K |
| | Wood | 3.29 W/m$^2$K | 16 kJ/m$^2$K |

**Source**: based on Eletrobras (2019) and Weber (2018).

Table 2 – **Orientation of the window and tone of the walls**

| Parameters | Values |
|---|---|
| Orientation - azimuth | North (0°), Northeast (45°), east (90°), Southeast (135°), South (180°), Southwest (225°), West (270°), Northwest (315°) |
| Colour - thermal absorptance | Light (0.3), medium (0.5), dark (0.7) |

**Source**: based on Eletrobras (2019).

An infiltration rate of 0.3 air changes per hour was added, considering a tight envelope construction (BOBENHAUSEN, 1994). The two idfs differ from each other in terms of the presence or absence of the ground object. In the second step, the idf with the ground object was used to model detached houses and ground-floor apartments, and the idf without the ground object was used to model upper-level apartments. The ground floor was modelled based on the Site:GroundDomain:Slab (ELI *et al.*, 2019). In the upper-level apartments, the surface representing the roof in the single zone was set as outdoors while it was set as adiabatic for the other apartments. In the third step, each case (or idf) representing each air conditioner received the dwelling and air conditioner information. Since the Brazilian survey on Ownership of Appliances and Consumption Habits (ELETROBRAS, 2019) report did not provide the colour of the roof and the type of floor, it was based on the materials described in Weber (2018). A medium colour (thermal absorptance of 0.5), thermal transmittance of 4.43 W/m$^2$K, and thermal capacity of 160 kJ/m$^2$K were considered, representing a ceramic tile floor with a mortar and concrete subfloor.

The air conditioner was modelled with the object HVACTemplate:Zone:PTHP (packaged terminal heat pump). The pattern of use and thermostat temperatures were defined according to the mean values informed by inhabitants (18 ºC for heating and 24 ºC for cooling). The cooling/heating capacity and the coefficient of performance (COP), respectively, were modelled according to the mean and mode values of the same air conditioners given in the PBE database.

Internal loads representing occupation and lighting system usage were also added. Two people in the thermal zone represented the occupation, with a metabolic rate of 81 watts each. The air conditioner was considered to be in operation from 9 pm to 8 am. For the lighting system, the usage considered was from 6 am to 8 am and from 7 pm to 10 pm, with a power density of 5 W/m  (ABNT, 2021).

After the characterisation process, the idfs were grouped and simulated according to the city, considering the TMYx (Typical Meteorological Year derived from hourly weather data through 2017) 2003-2017 weather files obtained from the ClimateOneBuilding (2019). For the cities without a representative TMYx file, the nearest city with a TMYx file located in the same Standard 169 (AMERICAN…, 2013) climatic zone was considered. The analyses considered all the cities in the Brazilian survey on Ownership of Appliances and Consumption Habits (ELETROBRAS, 2019).

Some air conditioners in the survey database were classified as occasional use, meaning they were not used in a particular daily period. In these cases, the consumption was estimated based on the building energy simulation approach. Firstly, it was considered that, on average, the hours of daily use of these air conditioners were the same as those of the air conditioners with the defined period of use. For each air conditioner with occasional use, the value for the hours of daily use was then added based on the average time of use of all air conditioners in the same region. In the second step, a mean monthly electricity consumption per hour of all simulated air conditioners was obtained according to the climatic zone (AMERICAN…, 2013) and frequency of use (which informs the number of days that the appliance is used in a given month). Information on the frequency of use of the air conditioners set as ‘occasional use’ was also provided. In the third step, these air conditioners received one of the mean monthly electricity consumption per hour of each month, according to their climatic zone and frequency of use. These values for the monthly electricity consumption per hour of use were then multiplied by the mean hours of daily use obtained in the first step, giving an estimate for the monthly consumption of all air conditioners with occasional use. Finally, the electricity consumption of the air conditioners with occasional use was added to the consumption of the simulated cases to obtain the annual electricity consumption of air conditioners.

## Step 3: projection

In Step 3, the electricity consumptions associated with each appliance were estimated, aiming to reflect the consumption of all dwellings in each state. The survey calculated the sample size of each Brazilian state to obtain a confidence level of 95% and a sampling error of 4%. It was thus considered that the dwellings of the survey database were representative of the Brazilian residential sector and the values for the end use electricity consumption were estimated for each state according to Equation 10.

$$Cproj = C_{end\,use}\ X\ \frac{DW_1}{DW_2}$$ Eq. 10

Where:

*Cproj* is the annual estimated electricity consumption of the end use in a given state (kWh);

$C_{end\text{-}use}$ is the annual electricity consumption of the end use obtained in the Step 2;

$DW_1$ is the total number of dwellings in the state, based on IBGE (2019b); and

$DW_2$ is the number of dwellings in the survey database that were located in the same state.

### Step 4: percentage of electricity consumption for end uses

In Step 4, the percentage of electricity consumption was determined associated with each end use concerning the residential sector's actual annual electricity consumption, on a regional and national basis, using Equation 11.

$$Perc_{end\,use} = \frac{\sum_{UF} Cproj_{UF}}{C_{real}}\ x\ 100$$ Eq. 11

Where:

$Perc_{end\text{-}use}$ is the regional or national percentage of annual electricity consumption for the end use;

$Cproj_{UF}$ is the annual electricity consumption for the end use estimated for a state (kWh);

$C_{real}$ is the real regional or national annual electricity consumption of the residential sector (kWh), obtained from EPE (2010); and

*UF* is the state.

The values obtained for the national percentage of electricity consumption for each end use were then compared with the values presented by Ghisi, Gosch and Lamberts (2007) and Fedrigo *et al.* (2009), which were based on a previous survey on Ownership of Appliances and Consumption Habits, conducted between 1997 and 1998 and between 2004 and 2006, respectively. A comparison between the three studies may better understand the electricity consumption profile in the Brazilian residential sector and help identify the parts of the proposed method that need further improvement.

## Comparison with previous studies

This paper considered an estimate of electricity consumption associated with air conditioning systems to assess the differences between the estimates of electricity consumption obtained with building energy simulation and electricity consumption equations, using Equation 12:

$$C_{AC} = \sum_{type,cap,op} Prop_{type,cap,op}\ x\ C_{type,cap,op}\ x\ T\ x\ 12$$ Eq. 12

Where:

$C_{AC}$ is the annual electricity consumption of air conditioners (kWh);

$Prop_{type,cap,op}$ is the proportion of air conditioners of the same type (window or split), thermal capacity and operation mode (with or without reversed cycle);

$C_{type,cap,op}$ is the representative monthly electricity consumption (in kW), according to mean values of the same air conditioners presented in the PBE database; and

*T* is the hours of monthly use of all air conditioners (hours).

For the air conditioners with occasional use, it was considered that their hours of daily use were equal to the average hours of daily use of the air conditioners that had this information. The projection and percentages of electricity consumption were obtained according to the equations previously presented (Equations 10 and 11).

# Results

## Regional ownership by appliance

The ownership data for the nine appliances considered in this analysis are detailed in this section. Figure 3 shows the regional mean values for the ownership of electric showers, fans, and air conditioners in the Brazilian survey on Ownership of Appliances and Consumption Habits report (ELETROBRAS, 2019) normalised to the number of dwellings in each state.

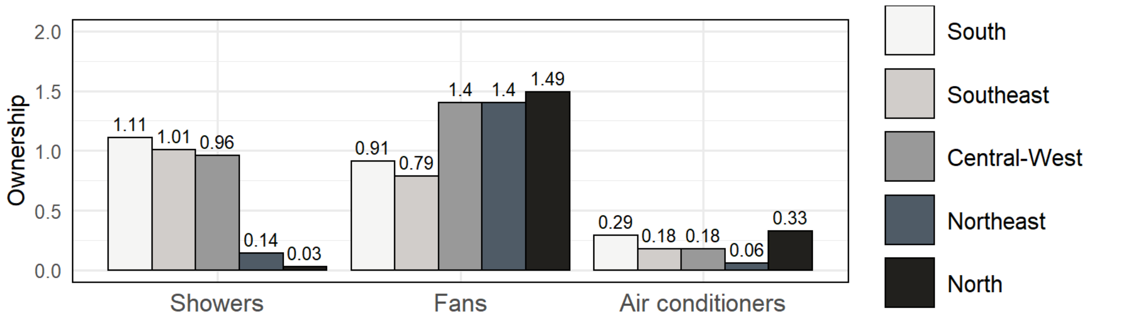
The South and Southeast regions, the coldest regions in Brazil, have the highest ownership of electric showers, the main appliance for domestic water heating in the country, and the lowest ownership of electric fans. The Northeast and North regions, by contrast, have the lowest ownership of electric showers and the highest of electric fans, alongside the Central-West region. The level of ownership of air conditioners is still low in Brazilian dwellings; the North region has the highest ownership, followed by the South region, where the dwellings tend to have air conditioners with reverse cycle, for cooling in summer and heating in winter. Figure 4 shows the ownership of other appliances analysed in this paper, except for light bulbs.

The North and Northeast regions have the lowest level of ownership of washing machines, microwave ovens and freezers, and refrigerators and televisions alongside the Central-West region. The ownership of these appliances is not related to the climate but may be affected by household income, which explains the lower ownership in the North and Northeast regions.

## Bottom-up regional estimates of annual electricity consumption by appliance

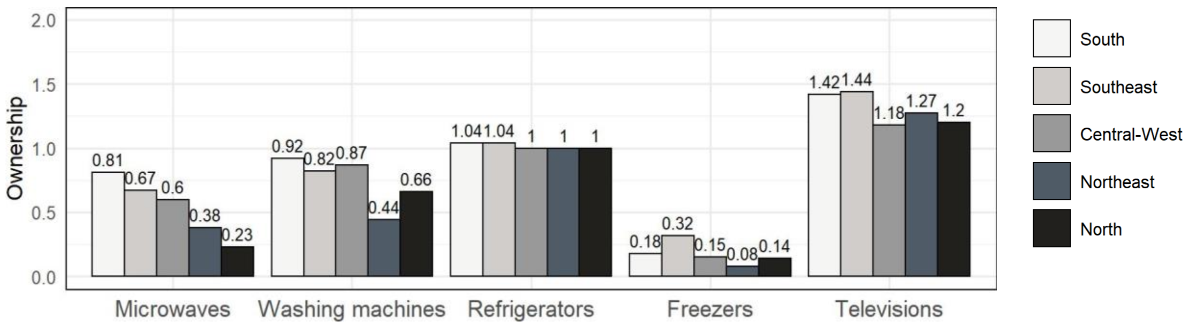
The differences in ownership, usage pattern, and technology can significantly impact the electricity consumption profile for the five regions. This section presents, for each appliance, the estimation of annual electricity consumption and their percentage of electricity consumption.

Figure 3 - **Regional ownership of electric showers, fans, and air conditioners**




**Source**: based on Eletrobras (2019).

Figure 4 - **Regional ownership of microwaves, washing machines, refrigerators, freezers, and televisions**




**Source**: based on Eletrobras (2019).

## Light bulbs

In the case of light bulbs, the percentage of electricity consumption is below 12% in all regions, as seen in Table 3. Figure 5 shows the mean level of ownership of light bulbs by technology in the present survey database and its previous version, released before the popularisation of LED light bulbs. LED technology for light bulbs has reduced the electricity consumption associated with this appliance, especially in the South region.

## Refrigerators and freezers

The percentage of annual electricity consumption related to refrigerators is above 20% in the five regions, and similar values were obtained in four regions: South (21.3%), Southeast (21.4%), Central-West (22.8%), and North (20.1%), as shown in Table 4. The lower variation was expected since the regional level of ownership of refrigerators is almost the same. Moreover, this appliance tends to be continuously turned on, regardless of the region. Freezers are not commonly present in Brazilian dwellings. Therefore, they account for a lower percentage of the electricity consumption in the residential sector.

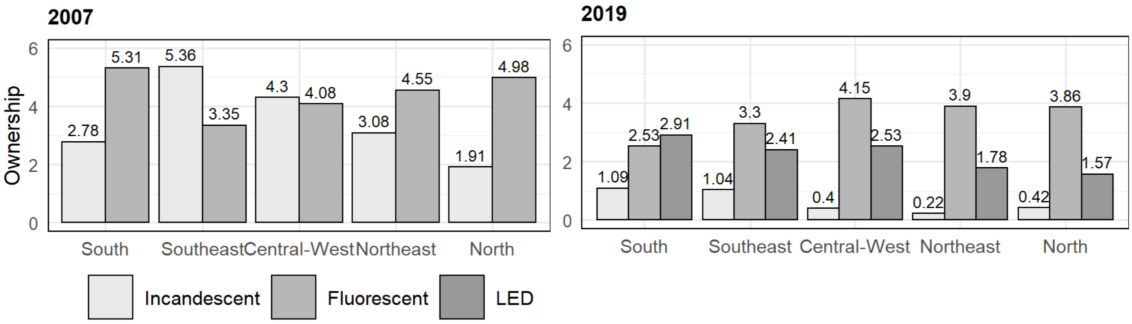
## Televisions

Televisions accounted for over 12% of the electricity consumption in all regions, as shown in Table 5. This result is related to televisions and is very popular in Brazilian dwellings even with new technologies, such as smartphones, notebooks, and tablets.

Table 3 - **Annual electricity consumption data for light bulbs by region**

| Information | South | Southeast | Central-West | Northeast | North |
|---|---|---|---|---|---|
| Annual Electricity Consumption (TWh) | 2.6 | 5.5 | 0.7 | 2.2 | 0.7 |
| Percentage (%) | 11.9 | 8.2 | 5.6 | 7.8 | 7.2 |

Figure 5 - **Mean regional ownership of light bulbs by technology**




**Source:** Procel (PROGRAMA..., 2007).

Table 4 - **Annual electricity consumption data for refrigerators by region**

| Information | South | Southeast | Central-West | Northeast | North |
|---|---|---|---|---|---|
| Annual Electricity Consumption (TWh) | 4.7 | 14.3 | 2.7 | 7.4 | 1.9 |
| Percentage (%) | 21.3 | 21.4 | 22.8 | 26.7 | 20.1 |

Table 5 - **Annual electricity consumption data for televisions by region**

| Information | South | Southeast | Central-West | Northeast | North |
|---|---|---|---|---|---|
| Annual Electricity Consumption (TWh) | 3.5 | 9.4 | 1.4 | 4.8 | 1.1 |
| Percentage (%) | 15.9 | 14.1 | 12.1 | 17.3 | 12.1 |

### Microwave ovens and washing machines

The regional values for the electricity consumption of microwave ovens and washing machines are considerably lower compared with the previously discussed appliances, as shown in Table 6 and 7. Despite the lower levels of ownership of both appliances, their lower annual electricity consumption is related to two factors: low number of hours of daily use for microwave ovens and low frequency of use for washing machines.

### Electric showers

For electric showers, there is a significant increase in the percentage of electricity consumption in the regions with cooler climatic zones, ranging from 0.5% in the North region to 33.8% in the South, as shown in Table 8. The regional variations are primarily reflected by the climate differences among regions, which influence the ownership of electric showers and the temperature at which the appliance is commonly used. The water temperature determines the power needed to heat the water and, therefore, it influences its electricity consumption.

### Electric fans

The electricity consumption of electric fans also varied considerably among regions (Table 9), with lower values in the South and Southeast regions. The Northeast region presented the highest percentage of electricity consumption (12.5%) associated with electric fans, followed by the Central-West region (10.0%). The North region presented the third highest value (9.7%). However, it does not mean that the need for cooling is lower when compared to the Northeast and Central-West regions since air conditioners are also used for the same purpose.

Table 6 – **Annual electricity consumption data for microwave ovens by region**

| Information | South | Southeast | Central-West | Northeast | North |
|---|---|---|---|---|---|
| Annual Electricity Consumption (TWh) | 0.8 | 1.2 | 0.1 | 0.3 | 0.0 |
| Percentage (%) | 3.7 | 1.8 | 1.0 | 1.2 | 0.4 |

Table 7 – **Annual electricity consumption data for washing machines by region**

| Information | South | Southeast | Central-West | Northeast | North |
|---|---|---|---|---|---|
| Annual Electricity Consumption (TWh) | 0.8 | 1.6 | 0.3 | 0.4 | 0.2 |
| Percentage (%) | 3.6 | 2.3 | 2.3 | 1.3 | 1.6 |

Table 8 – **Annual electricity consumption for electric showers by region**

| Information | South | Southeast | Central-West | Northeast | North |
|---|---|---|---|---|---|
| Annual Electricity Consumption (TWh) | 7.4 | 15.9 | 2.0 | 0.7 | 0.0 |
| Percentage (%) | 33.8 | 23.8 | 16.5 | 2.6 | 0.5 |

Table 9 – **Annual electricity consumption for electric fans by region**

| Information | South | Southeast | Central-West | Northeast | North |
|---|---|---|---|---|---|
| Annual Electricity Consumption (TWh) | 0.2 | 0.4 | 1.2 | 3.5 | 0.9 |
| Percentage (%) | 0.8 | 0.7 | 10.0 | 12.5 | 9.7 |

## Air conditioning

Table 10 reports the values for the annual percentage of electricity consumption of air conditioners by region. Due to the lower level of ownership of air conditioners in the survey database, the percentage of electricity consumption is lower when compared to most of the other appliances considered in this study. However, the North region obtained a significant value of 11.8%, the third highest percentage of electricity consumption for the nine appliances analysed in the region.

The North and South regions have the highest levels of ownership of air conditioners (0.33 and 0.29, respectively). However, the percentage of electricity consumption in the North is significantly higher due to its hotter climate. More than 60% of the air conditioners are used in the North region annually from six to seven days a week. The Northeast follows a similar pattern, with more than 55% of the air conditioners used from six to seven days a week in all months.

## Regional estimates considering all appliances and limitations of the estimates

Figure 6 shows the regional electricity consumption values for the nine appliances and their annual electricity consumption.

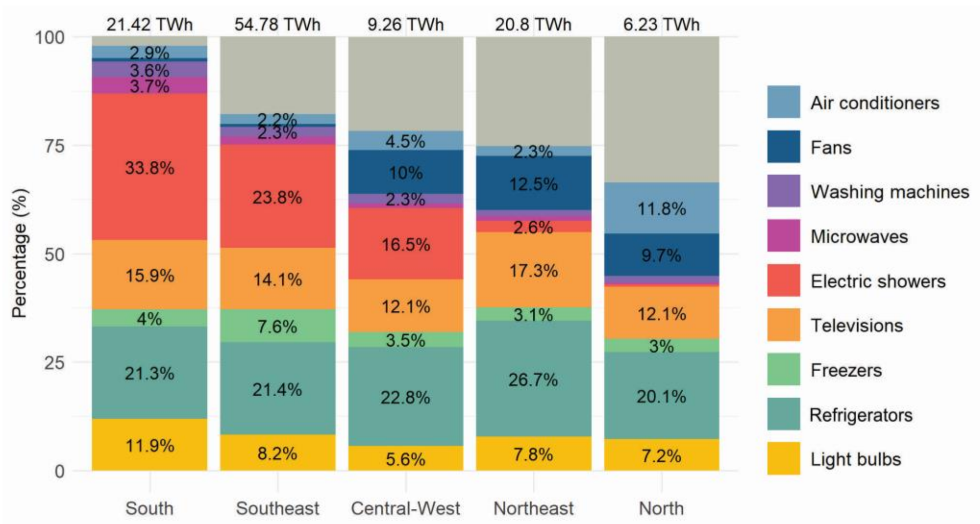
Electric showers are the principal consumers in the South (33.8%) and Southeast (23.8%) regions, while refrigerators are the principal consumers in the Central-West (22.8%), Northeast (26.7%), and North (20.1%) regions. The lowest electricity consumption was observed for electric fans in the South (0.8%) and Southeast (0.7%) regions and microwave ovens in the Central-West (1.0%), Northeast (1.2%), and North (0.4%) regions. The main regional variations in electricity consumption were observed for electric showers, fans, and air conditioners. The appliances are related to climate conditions.

The total percentage of electricity consumption of the nine appliances presented in Figure 6 also varied among the five regions: 97.0% in the South, 82.0% in the Southeast, 78.4% in the Central-West, 74.9% in the Northeast, and 66.4% in the North. It means that either the estimates for the electricity consumption of one or more appliances are overestimated in the coldest regions, or they are underestimated in the hottest regions. It also could be related to the non-consideration of the climate differences in the electricity consumption equations for refrigerators and freezers. Both of these appliances consume less electricity in colder climates as the less difference there is between inside and outside, the less energy is needed to maintain the inside temperature (refrigerator and freezer).

Table 10 - **Annual electricity consumption data for air conditioners by region**

| Information | South | Southeast | Central-West | Northeast | North |
|---|---|---|---|---|---|
| Annual Electricity Consumption (TWh) | 0.6 | 1.4 | 0.5 | 0.6 | 1.1 |
| Percentage (%) | 2.9 | 2.2 | 4.5 | 2.3 | 11.8 |

Figure 6 - **Annual electricity consumption of the nine appliances by region**



Thus, a lower percentage of electricity consumption is expected for these appliances in the South and Southeast regions. The values for the regional percentage of electricity consumption for refrigerators obtained using the method presented by Cardoso, Nogueira and Haddad (2010) are shown in Figure 7.

The method proposed by Cardoso, Nogueira and Haddad (2010) shows that the coldest regions tend to have a more significant reduction in the percentage of electricity consumption, which may reduce the regional differences. However, the equation presented by Cardoso, Nogueira and Haddad (2010) is applied only to refrigerators. It does not consider the degradation of the appliance over time, which tends to increase the electricity consumption. Furthermore, the equation is based on a fixed internal temperature (5 °C), different in every refrigerator. Because of these limitations, this study did not consider regional climate differences in the estimation approach. However, it became evident that an equation that estimates the electricity consumption of refrigerators and freezers considering the Brazilian climate differences, the degradation of the appliance over time, and the thermostat usage needs to be developed.

In this regard, another factor to consider is using a single building energy simulation model to represent the rooms in which the air conditioners are located since the survey database does not provide sufficient information to model the entire dwelling or the operation of the windows. The single zone modelled in this study has two exterior walls and two interior walls considered adiabatic. The window has a fixed size and was considered to be closed throughout the day. These features may have lowered the thermal exchange between the outside and inside environments of the building, especially in hotter climates, reducing the electricity consumption required for cooling.

The grey area of remaining consumption corresponds to that amount of electricity consumption not reached by the nine appliances. The residential sector varies in terms of types of electric equipment. Some types of equipment were not considered in this study and represent a significant average possession. For example, according to the Brazilian survey on Ownership of Appliances and Consumption Habits (ELETROBRAS, 2019), the national average ownership of blenders was 0.85, that of electric irons was 0.44, that of DVDs (Digital Versatile Disc), and similar was 0.37, the for sandwich makers was 0.32, for notebooks was 0.29 and for computers was 0.18.

## National estimation and comparison with previous studies

Despite the limitations related to refrigerators, freezers and air conditioners, most of the national results obtained in this study were consistent with those reported by Ghisi, Gosch and Lamberts (2007) and Fedrigo *et al*. (2009). Both studies have a similar pattern, as described in Figure 8. Figure 8 shows the national percentage of electricity consumption obtained in the three studies, considering only the nine appliances considered herein.

In the three studies, refrigerators were the largest electricity consumers, obtaining 33% in Ghisi, Gosch and Lamberts (2007), 37% in Fedrigo *et al*. (2009), and 22.5% in the study reported herein, followed by electric showers (20%, 19%, and 18.9%, respectively). The lowest percentages for electricity consumption were observed for washing machines and microwave ovens. Televisions were found to be the third largest electricity consumers in this study (14.8%). In comparison, according to Fedrigo *et al*. (2009) and Ghisi, Gosch and Lamberts (2007) they were the third (12%) and sixth (6%) largest, respectively. In this study, light bulbs were the fourth largest consumers (8.4%), and in Fedrigo *et al*. (2009) and Ghisi, Gosch and Lamberts (2007) they were the fourth (7%) and third (11%) largest. Since the estimates of Ghisi, Gosch and Lamberts (2007) are based on survey research carried out in the 1990s, the percentages are expected to be higher for light bulbs and lower for televisions, since incandescent light bulbs and CRT (cathode ray tube) televisions were more common at that time.

The most considerable difference between the estimates published by Ghisi, Gosch and Lamberts (2007) and those of the other two studies was observed for air conditioners. In this study and Fedrigo *et al*. (2009), the percentages were lower than 4%, while Ghisi, Gosch and Lamberts (2007) reached 10%. According to the authors, this latter value seems to be overestimated since the average ownership of air conditioners during the survey research conducted between 1997 and 1998 was 0.08.

Figure 7 - **Percentage of electricity consumption for refrigerators**

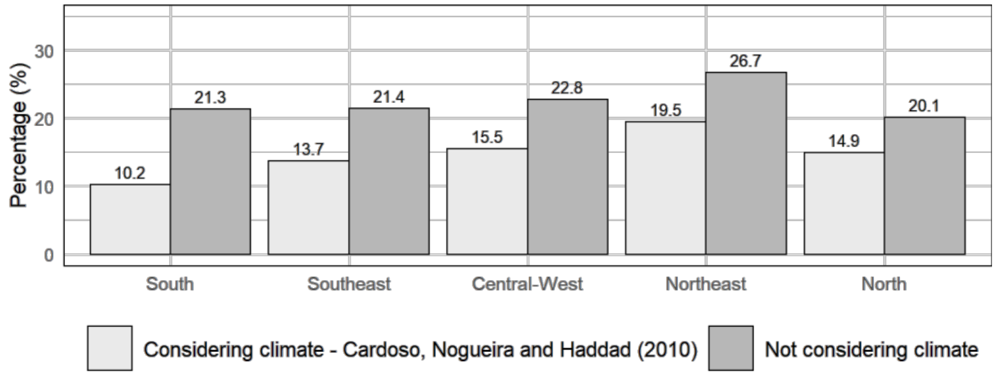
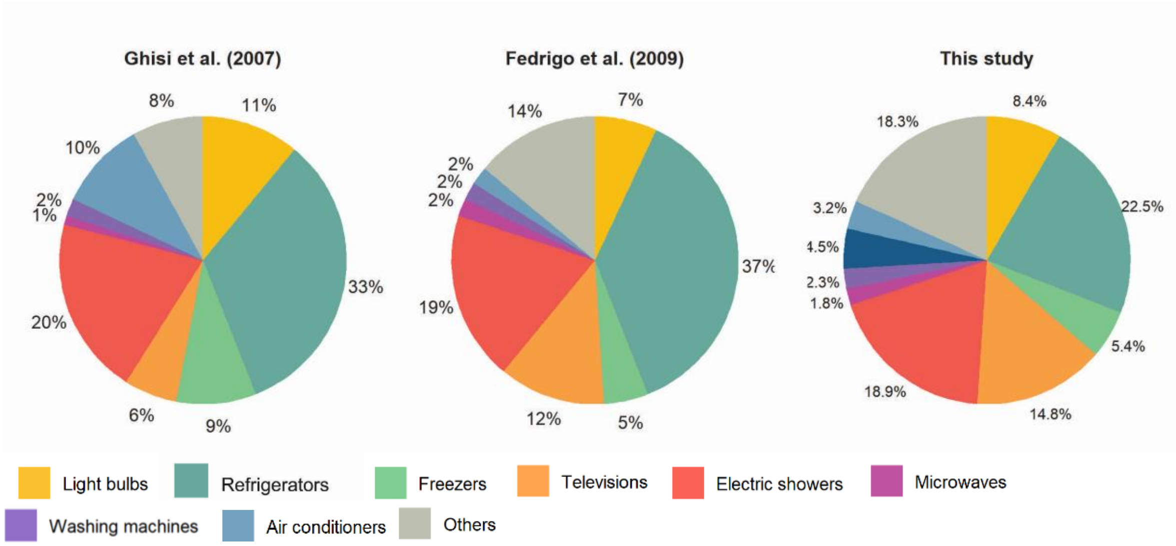



Figure 8 - **Comparison between national values for percentage of electricity consumption of different appliances**

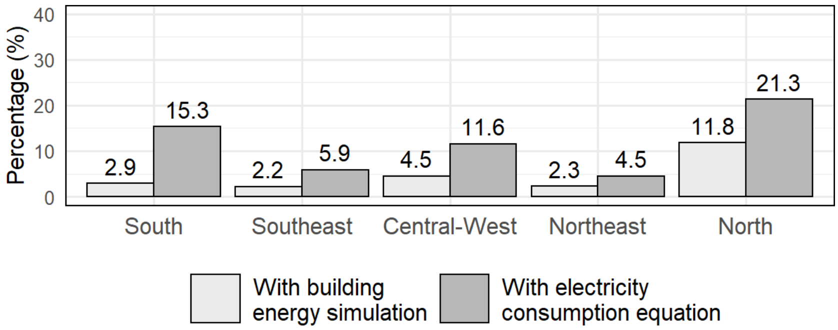



**Sources:** Ghisi *et al.* (2007) and Fedrigo *et al.* (2009).

It is essential to mention that the ownership of air conditioners has been increasing over time, reaching 0.18 in the dwellings included in the 2019 survey report. A Technical Note on the Use of Air Conditioners in the Brazilian Residential Sector (EMPRESA…, 2010) was published by the Energy Research Company (EPE). The main goal of the EPE is to support the Brazilian Ministry of Mines and Energy (MME) with energy policies and to ensure the basis for sustainable development of the country's energy infrastructure. The technical report estimates that the ownership of air conditioners in 2017 was 0.40, which is more than double the ownership given in the 2019 survey report (0.18). Moreover, the national percentage of electricity consumption for air conditioners reached 14% in 2017, which is much higher than the percentage found in this study.

The regional and national percentages of electricity consumption associated with air conditioners are the most controversial topic related to end uses in the Brazilian residential sector, and new research projects in this area should be encouraged. The proposed method provides an essential incentive as it shows that, despite the limitations in the survey database, it is possible to perform building energy simulations on a large scale based on the data provided by the survey on Ownership of Appliances and Consumption Habits (ELETROBRAS, 2019). Building energy simulation seems appropriate since it allows actual weather data for the location under analysis, which would not be possible with electricity consumption equations. Figure 9 allows a comparison between the estimated values for the percentage of electricity consumption associated with air conditioners obtained with building energy simulations and with electricity consumption equations. The national percentage for the electricity consumption of air conditioners obtained with the equation approach is 8.62%, still less than the 10% reported by Ghisi, Gosch and Lamberts (2007).

Figure 9 – **Comparison between regional percentages obtained for electricity consumption of air conditioners**




The use of the electricity consumption equation provided significantly higher percentages compared with the building energy simulation approach. The values for the representative electricity consumption used in the equation were based on mean values for the electricity consumption of air conditioners given in the PBE database, which were estimated using a calorimeter considering external and internal temperatures of 35 °C and 26.7 °C, respectively (INSTITUTO…, 2011). This temperature difference is much higher than those in most Brazilian regions, especially at night, when most air conditioners operate in Brazil, thus leading to electricity consumption. As the equation does not consider the climate differences, the South region (the coldest in Brazil) presented a much higher percentage of electricity consumption, having the second most significant level of ownership of air conditioners.

It is essential to mention that the percentage of use of air conditioners systems has been increasing due to changes in consumption habits, reaching an estimated value of 14% in the residential sector, according to EPE (EMPRESA…, 2010). Moreover, due to the rise in global temperatures, especially in developing countries with tropical climates, such as Brazil, a significant increase in the demand for air conditioners is expected in the coming years (ASSOCIAÇÃO…, 2019). Further analysis regarding the electricity consumption of air conditioners related to end uses in the Brazilian residential sector is essential to avoid misuse and promote energy conservation in buildings.

# Conclusions

Although collecting data on electricity end uses in the Brazilian residential sector is challenging, the results obtained in this study are close to the values expected for most appliances. Nationally, refrigerators were the appliance with the highest percentage of electricity consumption (22.5%), followed by electric showers (18.9%), televisions (14.8%), light bulbs (8.4%), freezers (5.4%), fans (4.5%), air conditioners (3.2%), washing machines (2.3%) and microwave ovens (1.8%).

However, the results for refrigerators, freezers, and air conditioners highlight two features of the model that need further improvement: the non-consideration of climate conditions in the electricity consumption equations for refrigerators and freezers and the simplification of the building energy simulation model for air conditioning. These deficiencies are associated with external factors that lie outside the scope of this study, related to the lack of reliable climate-related electricity consumption equations for refrigerators and freezers and insufficient data in the survey database to model the entire dwelling and the window operation. Even with this lack of data, the use of energy simulation to estimate the electricity consumption associated with air conditioning was a more reliable approach since it allowed the consideration of actual weather data on the location of the dwellings. Furthermore, the energy simulation model's infiltration rate of 0.3 air changes per hour should be varied to represent more reliability to the Brazilian dwellings.

Regionally, appliances for which the ownership and pattern of use are climate-related (electric showers, air conditioners, and fans) presented a significant variation in the percentage of electricity consumption. Electric showers varied from 33.8% in the South to 0.5% in the North. The air conditioners varied from 11.8% in the North to 2.2% in the Southeast. The electric fans varied from 12.5% in the Northeast to 0.7% in the Southeast. These variations showed that the climate is an essential factor regarding changes in the regional electricity consumption of the Brazilian residential sector.

Technological advances also play a role. In the case of televisions, the LED and LCD (liquid-crystal display) technologies, which have replaced CRT over the decades, may have increased the electricity consumption of this appliance due to the larger screen sizes. Technological advances do not necessarily lead to a reduction in electricity consumption.

The changes in electricity consumption noted herein highlight the importance of obtaining up-to-date bottom-up estimates to understand better the use of electricity in the Brazilian residential sector. Furthermore, the developed model shows that it is possible to obtain reasonable estimates of electricity consumption with the survey database. Moreover, it should motivate new approaches based on the proposed method.

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