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The multidimensionality of energy poverty in Brazil: A historical analysis

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ABSTRACT

The different dimensions that characterize energy poverty can be assessed by a Multidimensional Energy Poverty Index (MEPI). This study adapts and calculates MEPI for Brazil, which contributes to understanding the evolution of energy poverty incidence and intensity in the country. Using three different energy dimensions – *physical access*, *appliances ownership*, and *affordability* – we calculate MEPI for the 2002–2018 period. Results show that, despite a significant improvement in modern energy fuel access and, in rates of some primary *appliance ownership*, Brazil still shows a significant prevalence of energy poverty. Problems related to *affordability* have not been widely solved, and nowadays this remains the main issue: 11% of households still live in conditions of energy poverty, and in rural areas this number reaches 16%. Taking into account Brazil's social and geographic heterogeneity, we characterize energy poverty across different regions and socioeconomic groups. Results show that isolated areas in the northern region are those most lacking in energy services. We also underscore the income inequality that relates to conditions of energy poverty, and conclude that non-energy poor households tend to have an income at least twice as high as that of households considered energy poor.

1. Introduction

Guaranteeing access to affordable, reliable, sustainable, modern energy services for all is an important challenge for the 21st-century and it has become a stand-alone goal of the 2030 Agenda with Sustainable Development Goal (SDG) seven. Energy is critical for achieving decent living standards (Rao et al., 2019a) and satisfying basic human needs (Doyal and Gough, 1991). Assessments of the interlinkages between SDG 7 and other SDGs have highlighted the central role of energy in achieving sustainable development (McCollum et al., 2018). However, as of 2019, about 770 million people still lacked electricity, and 2.8 billion used harmful and polluting cooking fuels (IEA, 2020; Energy Sector Management Assistance Program (ESMAP), 2020).

Energy poverty can be defined as a household's inability to achieve certain levels of energy services, also known as energy deprivation (Bouzarovski and Petrova, 2015). There are many different approaches to understanding this problem, which can be described by means of a driving force perspective, an energy end use perspective, or an observation of the consequences related to energy deprivation (Bouzarovski and Petrova, 2015). González-Eguino (2015) describes three alternative but complementary approaches to measure energy poverty. These approaches consider that a person is energy poor if energy cannot be used because of technological, economic, or physical limitations. The technological approaches indicate that energy poverty is related to infrastructure constraints in accessing modern energy fuels. Lack of connection to an electrical grid and extensive use of biomass for cooking are central to characterizing energy poverty in developing countries, where access to primary energy is a common problem (González-Eguino, 2015; Dagnachew et al., 2019; Pachauri et al., 2004), and has been widely used as a proxy for measuring energy poverty (Bouzarovski and Petrova, 2015; González-Eguino, 2015; Mendoza et al., 2019; Thomson and Snell, 2013; Mould and Baker, 2017).

For developed economies structural access is no longer a major concern. The literature focuses on affordability and uses expenditure-based indicators to measure energy poverty (Pachauri et al., 2004; Thomson and Snell, 2013; Sánchez-Guevara Sánchez et al., 2020; Meyer et al., 2018). When focusing on the economic dimension, people are considered energy poor or fuel poor when they cannot pay for essential

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energy services (Waddams Price et al., 2012; Randazzo et al., 2020; Romero et al., 2018).

Physical threshold approaches (González-Eguino, 2015), also known as engineering-based (Pachauri et al., 2004) approaches, estimate the minimum level of energy consumption required to fulfill basic needs (González-Eguino, 2015; Dagnachew et al., 2019; Pachauri et al., 2004; Ribas et al., 2017, 2019), such as lighting, cooking and food conservation. This latter approach depends on many different parameters which are specific to each energy use (Nico, 2020; Faiella and Lavecchia, 2019). However, these indices do not reveal important aspects of consumption relating to cultural and behavioral attributes across subnational regions and socioeconomic groups (González-Eguino, 2015; Barnes et al., 2011). Despite the focus on basic needs, threshold indicators tend to overlook the complexity of energy poverty and its fine points, since social relationships, norms, and behaviors shape how people benefit from access to energy services (Day et al., 2016). Understanding energy poverty in all its components requires a more comprehensive metric (Day et al., 2016; Pachauri and Spreng, 2011) that goes beyond access and expenditure (Berry, 2018; Patrick NussbaumerMorgan et al., 2012) and accounts for its multidimensionality. The Multidimensional Energy Poverty Index (MEPI), described by Nussbaumer et al. (Patrick NussbaumerMorgan et al., 2012), and adapted to different research contexts and objectives (e.g. (Mendoza et al., 2019; Romero et al., 2018; Pachauri and Spreng, 2011; Patrick NussbaumerMorgan et al., 2012; Fabbri, 2019; Sadath and Acharya, 2017a; Papada and Kaliampakos, 2016),), helps to identify the multiple aspects in which a household can be energy-deprived in specific contexts (Sadath and Acharya, 2017b) and to better tailor domestic energy policies (Kowsari and Zerriffi, 2011).

In Brazil, research on energy poverty still overlooks its multifaceted nature, despite the fact that several initiatives in the country have guaranteed access to modern cooking fuels and electricity for low-income families (Coelho et al., 2018) (Table 1). The literature on Brazil's energy poverty focuses mainly on the implications of access and availability, social dynamics, or the effects of national policies to eliminate using traditional fuels (Mazzone, 2019; Pereira et al., 2010; Giannini Pereira et al., 2011). Economic dimensions have received little attention (Gioda, 2019a) and no study has explored energy poverty in terms of how energy services are used. Even the most recent literature on the multidimensionality of energy poverty in Brazil has not quantified the contribution of these additional dimensions (Mazzone et al., 2021a). Moreover, how a comprehensive notion of energy poverty varies across regions, states and income groups remains to be examined (Mazzone et al., 2021a; Pereira et al., 2021).

So far, Brazil has succeeded in improving accessibility to electricity and other modern fuels, such as liquefied petroleum gas (LPG). However, accessibility alone is insufficient for satisfying a household's basic energy services. The recent severe economic crisis has led the number of people living in conditions of poverty and extreme poverty to levels of decades ago (de população e I. and IBGE, 2018), demonstrating that physical access to energy is only one aspect of reducing the country's energy poverty and widespread energy inequalities (Piai Paiva et al., 2019). The pre-Covid 19 economic disruption, coupled with the rising prices of LPG, forced people to return to using traditional, cheaper, pollutant energy fuels such as firewood, charcoal, and other collectible, flammable cooking materials (IBGE and SIDRA - Banco de Tabelas Estat í sticas, 2020; ANÍBAL et al., 2021; Felicio et al., 2021). The Covid-19 pandemic aggravated this situation even further by highlighting the country's persistent problem of energy poverty and the vulnerabilities of its families, which far surpass the sole problem of solving physical access. Such lessons are valuable for eradicating energy poverty, not only in Brazil but in other countries with similar socio-economic conditions. Understanding the broader context of energy-poor families helps in designing policies that have a higher chance of success (Papada and Kaliampakos, 2016), especially in countries characterized by chronically high inequalities. For example, it is critical to identify the profile of social groups that live under conditions of energy deprivation and their surrounding infrastructure (Mendoza et al., 2019; Aristondo and Onaindia, 2018a), because they are most likely to be pushed into energy poverty (Sharma et al., 2019).

This paper outlines a comprehensive quantitative picture of Brazil's multiple dimensions of energy poverty and their evolution over time. The MEPI is adapted to the Brazilian situation to quantify the number of the energy poor (prevalence) and the intensity of their condition (severity). Multidimensional indices make it possible to understand multiple features and to clearly describe the evolution of energy poverty (Patrick NussbaumerMorgan et al., 2012). MEPI was developed to be applicable to different kinds of contexts and for different objectives and analyses, for both developed (Aristondo and Onaindia, 2018a; Bollino and Botti, 2017; Okushima, 2017) and developing regions (Mendoza et al., 2019; Nico, 2020; Sadath and Acharya, 2017a; Pereira et al., 2021; Tait, 2017).

By taking account of the importance of social and regional heterogeneity within the country (de população e I. and IBGE, 2018; IBGE, 2017; PNUD IPEA, 2016; Mazzone, 2020a), we analyze results for different regions and socioeconomic groups. To our best knowledge, there is no previous literature that assesses historical multidimensional energy poverty indices in developing countries by focusing on their heterogeneity across regions, income groups, and between urban and rural areas. Studies at sub-regional and different income levels are important policy-orienting factors, as they can identify problems and concerns related to specific conditions.

The remainder of the paper is organized as follows. **Section 2** introduces the context of energy poverty in Brazil. **Section 3** presents the research method and describes the MEPI methodology, dimensions, and data source for the case study. **Section 4** provides the results, including sensitivity analyses. The discussion that follows in **Section 5** describes the limitations of physical access to modern energy sources in guaranteeing an eradication of the country's energy poverty and a socioeconomic characterization of households considered to be energy poor. We conclude by highlighting the main findings of this study and possible recommendations for developing policy.

2. Brazilian energy context

Literature on energy poverty in Brazil has focused on the continued use of firewood for cooking and the lack of access to electricity, especially in rural areas (Pereira et al., 2010; Giannini Pereira et al., 2011; Mazzone et al., 2019; da Silveira Bezerra et al., 2017). Although access to modern fuels in Brazil is currently considered universal (GRUPO DE TRABALHO DA SOCIEDADE CIVIL PARA, 2021), infrastructure and affordability issues still hinder the benefits of using it (Rao et al., 2019a; Mazzone, 2020a; Grottera et al., 2018). The persistent use of firewood and charcoal for cooking is highly associated with household financial constraints (Gioda, 2019b). Even though LPG is available for sale in almost every municipality in the country, low-income families often use both LPG and firewood for cooking (Coelho et al., 2018) primarily because of budget constraints (Coelho et al., 2018; de população e I. and IBGE, 2018) .[1] The affordability problem has been discussed since the 1970s, and different public policies (e.g., *Auxílio Gás*) have focused on the transition from firewood to LPG for cooking. Such policies were substituted by the *Bolsa Família* (BF) program in 2004, which grouped several social benefits to guarantee that families could afford a minimum basket of goods and services, including LPG. However, the monthly value of BF did not keep up with inflation and LPG price increases (Mazzone et al., 2019). In 2021 BF was discontinued and replaced by a new program called *Auxílio Brasil*, whose continuation

[1] There is, however, a cultural aspect of firewood consumption for cooking in some regions, which is not necessarily related to income (Mazzone et al., 2021b).

Table 1
Summary of the most important Federal Government social programs in Brazil (Author elaboration based on (do Brasil, 2021; Eletrobras, 2021; Ministério de Minas and Energia, 2021; BRASIL Presid ê ncia da Rep ú blica, 2002; Caixa Economica Federal and Família, 2021; da Cidadania and Único, 2021; Ministério da Cidadania, 2021).

Program	Duration	Main goal	Benefit	Target audience
Tarifa Social de Energia Elétrica (TSEE)	2010 - ongoing	Aids families in paying their electricity bills	Proportional discounts – according to monthly electricity consumption level – on households' electricity bills	Low-income*, indigenous and *quilombolas*** families
Auxílio Gás,	2002–2003	Assists low-income families in purchasing LPG	Bimonthly voucher	Low-income* families
	2021 - ongoing	Reduces the effect of cooking gas price increases on the budgets of low-income families	Bimonthly voucher	Low-income* families
Luz para Todos (LpT)	2003 - ongoing	Universalization of electric energy access and use	Physical access to electricity energy	Vulnerable families without access to electric energy
Bolsa Família (BF)	2003–2021	Helps families to overcome situations of poverty, extreme poverty and vulnerability	Direct income transfer program	Low-income* families
Auxílio Brasil	2021 - ongoing	Updates BF program: Helps families to overcome situations of poverty, extreme poverty and vulnerability	Direct income transfer program	Low-income* families

Note: * Low income is defined as families living with an income no higher than half of the minimum-wage (today BRL 1212 or US$ 232); **The *quilombolas* are groups the special cultural identity of being remnants of a racial-ethnic group formed by descendants of runaway slaves during the slavery period in the country and include other groups that lived in the so-called "quilombos".

after 2022 is still uncertain. Some studies argue that such cash-transfer policies have succeeded in making LPG more affordable for all, but evidence shows there have been no significant advances since 2021 (Coelho et al., 2018), when the government launched *Auxílio Brasil* (do Brasil, 2021). The ongoing use of firewood can be associated with the increase in LPG prices, which can cost up to 10% of a family's minimum wage income,[2] and the lack of subsidies to support its use (Coelho et al., 2018; Gioda, 2019a). This new program intends to complement social protection programs under the current context of high LPG prices as observed in 2021.

Electricity, like LPG, is available to nearly 100% of Brazilian households. In the last two decades, a policy to universalize electricity access in rural areas (IBGE and SIDRA - Banco de Tabelas Estat í sticas, 2020), *Luz para Todos* (LpT), extended it to approximately 16.9 million people (Eletrobras, 2021). However, despite these advances, there are still remote areas without access to electricity (Junior and Seabra, 2021), as well as quality issues with the service provided (GRUPO DE TRABALHO DA SOCIEDADE CIVIL PARA, 2021; ABR Energias Renov á veis, 2020). Moreover, people still have difficulty in being able to afford energy services, and access to social welfare programs is not always guaranteed (Grottera et al., 2018; Rao and Ummel, 2017). In 2010, the government created a program called *Tarifa Social de Energia Elétrica* (TSEE)[3] to subsidize electricity tariffs for low-income families and vulnerable groups.

The LpT and TSEE programs (Pesquisas, 2013a), along with economic growth and the expansion of other social programs, such as *BF* (2004–2021) (Grottera et al., 2018; Villareal and Moreira, 2016), contributed to increasing the prevalence of appliances, such as televisions and refrigerators (Pesquisas, 2013a) (Table 1). Further, after a significant drop in the share of the population living under extreme poverty conditions[4] from 11.5% in 2001 to 2.9% in 2014 (The World Bank, 2021), a subsequent economic disruption has led to a relapse into poverty of approximately 4 million people (IBGE and SIDRA - Banco de Tabelas Estat í sticas, 2020; The World Bank, 2021). Despite the increasing penetration of appliances in Brazilian households, ownership rates remain quite uneven, reflecting substantial socioeconomic disparities. Some appliances, such as washing machines, are not present in all family households and, in fact, are rare in homes of any kind (Grottera et al., 2018; Rao and Ummel, 2017).

3. Methodological approach

We have elaborated a three-step methodological approach. First, we define the critical dimensions of energy poverty in Brazil. Second, we gather the required data to measure the identified components. Lastly, we calculate the MEPI at the national and across regional levels, income groups, and urban/rural household situation.

3.1. Dimensions of energy poverty in Brazil

MEPI indicators assess the multidimensional nature of energy poverty through the lens of the energy services delivered to a household, such as lighting, communication and thermal comfort (Patrick NussbaumerMorgan et al., 2012). The fuel used and equipment ownership rates are the most commonly used metrics (González-Eguino, 2015; Sadath and Acharya, 2017b). According to Nussbaumer et al. (Patrick NussbaumerMorgan et al., 2012), each of MEPI's dimensions can be computed to characterize a society's incidence (*H*) and intensity (A) of deprivation (Mendoza et al., 2019; Patrick NussbaumerMorgan et al., 2012; Okushima, 2017). Considering the Brazilian context, and basing ourselves on the MEPI literature (Mendoza et al., 2019; Meyer et al., 2018; Patrick NussbaumerMorgan and Yumkella, 2011; Thomson et al., 2017), we analyze three different dimensions related to: (i) *physical access*; (ii) *appliances ownership*; and (iii) *affordability* (Table 2). Each dimension can vary from 0 to 1, with 1 as the highest degree of energy service deprivation, and 0 as non-energy deprivation. We relate one or more parameters to each dimension. From this perspective, each MEPI dimension corresponds to a deprivation type (RademaekersKoenYearwood et al., 2016), as demonstrated in (Table 3).

Physical access is related to the access to modern energy fuels and is evaluated by two parameters: cooking and electricity, the latter indicated by lighting services (Patrick NussbaumerMorgan and Yumkella, 2011). If a household declares using exclusively firewood or charcoal for cooking it is considered deprived (1), while if it declares using LPG, natural gas, or electricity to cook it is considered non-deprived (0). The metric does not consider fuel stacking, a common practice in Brazil (Coelho et al., 2018). Households that combine biomass with modern

[2] Final LPG prices in the state of Mato Grosso in Jun/21 compared to nationwide minimum wage in 2021, value followed on state level (ANP, 2022; G1, 2021).

[3] The TSEE program offers discounts on electricity tariffs for those registered in the *Cadastro Único*, with a monthly consumption below 220 kWh. The discount varies from 65% for low-income households consuming less than 30 kWh monthly, to 10% for monthly consumption between 110 and 220 kWh. For indigenous groups, the discount can reach up to 100% (Pesquisas, 2013a). On average, a Brazilian household consumes about 165 kWh/month, far above the 30-kWh of the highest discount range.

[4] World bank definition: poverty headcount rate at $1.90 a day (2011 PPP) (The World Bank, 2021).

Table 2
Dimensions and their associated parameters, with all their related information: weights (w_j, $j = \{py, ap, af\}$), indicators, variables, and thresholds.

Dimension	Parameters	Indicator	Variables	Threshold (deprived if)
Physical Access (py) $w_{py=1/3}$	Cooking (ck) $w_{py(ck)=1/6}$	Use of modern cooking fuels	Type of cooking fuel	Use of firewood or coal for cooking
	Electricity (ele) $w_{py(ele)=1/6}$	Reliable electricity access	Electricity access (grid connection)	Does not have grid connection
Appliance ownership (ap) $w_{ap=1/3}$	Space Cooling (cl) $w_{ap(cl)=1/9}$	Cooling appliance ownership	CDD normal Has AC	Does not own (weighted by CDD normal)
	Information/ Communication (i) $w_{ap(i)=1/9}$	Access to information	Has radio or TV Has internet access	Does not own Does not own
	Food Conservation (f) $w_{ap(f)=1/9}$	Food conservation appliance ownership	Has refrigerator or freezer	Does not own
Affordability (af) $w_{af=1/3}$	Energy Spending (exp) $w_{af(exp)=1/3}$	Energy expenditure ratio	Energy expenses/ total expenses	>2x local mean

Table 3
Parameters and their related energy services, and the social benefits of their uses (author elaboration based on (da Silveira Bezerra et al., 2017; Motta and Reiche, 2001; Rao et al., 2019b; World Bank, 2015)).

Parameter	Final energy service expression	Consequences
Cooking (ck)	cooking meals	Health (non-indoor pollution, better food options); reduces cooking time
Electricity (ele)	Basic condition for electrical use, such as light	General: IDH improvement; Light specific: Higher educational levels, improves leisure time at night, reduces gender gap; increases home productivity and small family business opportunities
Space Cooling (cl)	Thermal comfort Communication services	Health Higher educational levels;
Information/ Communication (i)	Information Entertainment	Improved leisure time (Tv, radio, internet)
Food Conservation (f)	Storing food	Health

fuels for security reasons, or financial constraints, are captured by the *affordability* dimension.

Accessibility to electricity is a family's first step in acquiring different appliances and benefits from a wide range of energy services. Indeed, electricity access is associated with many benefits for individuals and their communities (da Silveira Bezerra et al., 2017; Kanagawa and Nakata, 2008; Kanti Bose et al., 2013). We measure electricity access in terms of grid connection or self-generation systems. Our metric is a binary indicator taking the value of 1 if a household is entirely deprived, or a value of 0 if non-deprived.

Appliances ownership is the second dimension that can characterize situations of energy poverty. Considering the Brazilian context, we identify as the most important parameters food conservation, indoor thermal comfort, and access to information, communication and entertainment (Mendoza et al., 2019; Patrick NussbaumerMorgan and Yumkella, 2011). Refrigerators or freezers play an important role in people's livelihoods, as they allow the consumption of a variety of food types and the conservation of fresh foods. These appliances are one of the first adopted by a household, as they offer an essential energy service (Pesquisas, 2013b). Households are defined as deprived (1) if they do not own a refrigerator or a freezer. Entertainment, information and communication appliances allow people to fully participate in society (Barnes et al., 2016) and have been associated with a higher education level (Kanti Bose et al., 2013). Therefore, they are included as another parameter within the Appliance Ownership dimension. The information/entertainment metric was based on two indicators: access to television and access to the internet. Currently, television is being substituted or complemented by an internet connection, which can also supply communication services. A family is considered deprived of information (1) if they do not own a television or do not have internet access at home or from a mobile phone.

Brazil's hot and humid climate (IBGE, 2002) demands the inclusion of air-conditioning (AC) appliances as a dimension of energy poverty.[5] We consider ownership of AC appliances with a value of one and non-ownership with a value of zero. Space cooling can also be obtained with fans, which however work best in a hot, dry climate. Moreover, their energy requirements are much more limited than those of air-conditioning, which accounts more for cooling gaps (Mastrucci et al., 2019; Pavanello et al., 2021). Since air-conditioning is more important in hotter climates, we weigh the ownership parameter by the normalized Cooling Degree-Days of wet bulb (CDD_{wb}[6]) indicator, which we cal CDD_{normal}. CDD_{normal} varies from zero to one, with one representing the hottest conditions observed in the country. The last parameter is obtained by multiplying AC ownership by CDD_{normal}. To calculate the CDD_{normal} weight for the space cooling parameter, we use data that cover urban and rural areas and the State capitals (Mistry, 2019).

The third dimension, *affordability*, makes it possible to capture situations of limited capacity to actually use energy services because of financial constraints (Betto et al., 2020). Of the several expenditure-based indicators (Fabbri, 2019), we use here a relative metric indicating a situation of energy poverty (metric = 1) if the share of energy expenses over total expenses is above a certain threshold. This threshold is twice the mean of the energy expenses of the region where the household lives. Energy expenses include electricity, gas, and other fuels used in the home, but they do not include transport. Total expenditure considers all the collective costs related to a household, plus the expenses of each family member, such as transportation, health, travels, and others. As we intended to carry out a state-level analysis, the regional mean was calculated by state and urban/rural areas (Appendix A). We chose not to use national means, as energy use is linked to regional and cultural aspects (Rao and Ummel, 2017).

3.2. Database

We measure the indicators described in the previous section by using microdata on a household's expenditures and characteristics from the main national household expenditure survey (*Pesquisa de Orçamentos*

[5] Space heating is not considered in this work. In Brazil, ownership of indoor heating is concentrated only in its Southern region and in the State of São Paulo (Eletrobras/Procel and Resultados Procel, 2014, 2015). Here we work only with parameters that are relevant at the national level.

[6] Cooling degree-days (CDD) are calculated by adding the differences between a threshold temperature and a daily mean outdoor air temperature, on a monthly or yearly basis. The threshold temperature is defined to correspond to the set-point temperature when cooling is needed. CDD_{wb} is measured by taking into account humidity for wet-bulb conditions (Mistry, 2019; ASHRAE Atlanta, 2009).

Familiares – POF)[7] (IBGE). We use the three latest waves, 2002–2003, 2008–2009, and 2017–2018, covering a more than 15-year period, during which the country saw significant structural changes (de população e I. and IBGE, 2018; The World Bank, 2021). The survey is based on a sample of approximately 50,000 households[8] representative of all Brazilian homes. The questionnaires from the three waves contain information about each household's overall conditions, appliance ownership, characteristics of its members, and detailed income and expense data. The analysis was made at the state level,[9] differentiating between urban and rural areas.

3.3. Multidimensional energy poverty index (MEPI)

We calculate MEPI for Brazil by considering a population of n individuals and d dimensions, with $d = 3$. The matrix $X = [x_{ij}]$ represents the deprivation sum for each individual i for each dimension j, with i being a household identified in POF's year-by-year survey, and $j = \{py, ap\ or\ af\}$, as described before in Table 2. Each dimension j is weighted equally, therefore, $w_{py} = w_{ap} = w_{af} = 1/3$. The parameters are also equally distributed within each of the three dimensions. For example, cooking and electricity within the *physical access* dimensions are weighted equally, representing a final weight of 1/6 and 1/6, respectively[10]. Equally weighted dimensions can well describe time evolution of multidimensional indexes (Santos, 2019).

For the individual i, c_i is a weighted sum index representing its energy poverty score condition. It is calculated as shown in **Eq. (1)**:

$$c_i = \sum_{j=2}^{d=3} w_j x_{i,j} \tag{1}$$

where we defined:

$$\sum_{j=2}^{d=3} w_j = 1 \tag{2}$$

An individual is defined as multidimensionally energy poor if her/his energy poverty score c_i is above a specific defined deprivation cut-off, $c_i \geq k$, where $0 < k < 1$. The final score $c_i(k) = c_i$, if $c_i \geq k$ and $c_i(k) = 0$ if $c_i < k$. The higher k is, the greater the number of dimensions included to define a household as energy poor. When $k \sim 1$, the individual suffers from deprivation in all dimensions. We prioritize access to electricity or modern energy fuels as the threshold that defines energy poverty in Brazil. Thus, a household is considered energy poor if it does not have access to electricity or to LPG/gas for cooking. In that case, the cut-off chosen is $k = 1/6$ (Table 2), meaning that a household lacks at least one of the two parameters of the *physical access*.

The percentage of people considered energy poor according to the multiple dimensions (Table 2), and relative cut-off is defined as multidimensional head count ratio, H:

$$H = \frac{q}{n} \tag{3}$$

where q is the number of people identified as energy poor. The intensity of energy poverty, A is calculated as an average of the deprivation vector $c_i(k)$:

$$A = \sum_{i=1}^{n} \frac{c_i(k)}{q} \tag{4}$$

The multidimensional energy poverty index, MEPI, is then defined as the interaction between head count and intensity:

$$MEPI = H\ x\ A \tag{5}$$

MEPI is very sensitive to the choice of dimensions and parameters, as well as to the choice of the cut-off and the weights (Patrick NussbaumerMorgan et al., 2012). A sensitivity analysis for the cut-off values was performed by varying k from 0.1 to 0.9. The sensitivity analysis for the weight values is based on the rank exponent method (Sadath and Acharya, 2017b), which makes it possible to evaluate a range of combinations for w_j through an iterative approach for the three dimensions by using different ρ values. For the three dimensions (d) we ranked each one (r_j) according to its importance to the final measure. Given that, we calculate the dimension's weights (w_j) based on the normalized individual ranks (r_j), as shown by **Eq. (6)** (Roszkowska, 2013):

$$w_j = \frac{(d - r_j + 1)^\rho}{\sum_{l=1}^{d} (d - r_l + 1)^\rho} \tag{6}$$

The parameter ρ is used to describe weight distance, $\rho = 0$ results in equal weights. The higher ρ is, the steeper is the distribution of the weights. We ran this method for all possible rank combinations and for different ρ values. Rank positions for all the dimensions were combined with ρ limited to 2. Above $\rho = 2$, the dimension with the lowest weight became irrelevant (Appendix A).

4. Results for energy poverty in Brazil

4.1. Analysis of energy poverty dimensions

From Fig. 1, it is possible to note that the *physical access* dimension in Brazil has become almost universal, having grown considerably since 2002, mainly in rural areas. The same is observed for the *appliance ownership* dimension. Over time, the *affordability* dimension has not changed significantly.

Households deprived in the *physical access* dimension, which accounted for 5.5% of total rural households, primarily use firewood and charcoal for cooking. In 2017, lack of access to electricity reached 2.7% and 0.1% in rural and urban areas, respectively.

The *appliance ownership* dimension shows the greatest improvement over the period analyzed compared to other dimensions because of new electrical connections combined with Brazil's prosperous economic period during the early 2000s, when the average annual GDP growth rate (2000–2010) was 3.7%. Households deprived in the *appliance ownership* dimension decreased from 2002 to 2017, both in rural and urban localities, falling, respectively, from 45% to 9% and from 13% to 3%, attributable mostly to the widespread acquisition of televisions and refrigerators (Pesquisas, 2013b). Increased ownership of food conservation equipment reached 95% in rural households and 99% in urban households. The rate of AC ownership also increased along the observed period. But, unlike TVs and refrigerators, ACs are still not widespread in Brazil, that is largely dependent on local climate (Pavanello et al., 2021). The Northern region registers the highest temperatures in the country, as well as the highest rate of AC ownership compared to other regions.

Unlike the other two dimensions analyzed, the share of households deprived in the *affordability* dimension remained constant, around 9% throughout the assessed period. We noted a high degree of heterogeneity in all dimensions of energy poverty in Brazil, reflecting the differences

[7] POF is a survey of the Brazilian Institute of Geography and Statistics (*Instituto Brasileiro de Geografia e Estatística* – IBGE) that occurs since 1987 planned to be made each 6 years.

[8] Total households surveyed: 48,470 in 2002, 55,970 in 2008 and 57,920 in 2017.

[9] Brazil has 27 Federal Units, made up of 26 States and 1 Federal District.

[10] This is the dimension' weight divided by the number of parameters considered. Each dimension has a weight of 1/3. For the *physical access* dimension, each parameter has a final weight of 1/3 divided by two (numbers of parameters). For *appliance ownership*, each parameter has a final weight of 1/3 divided by three.

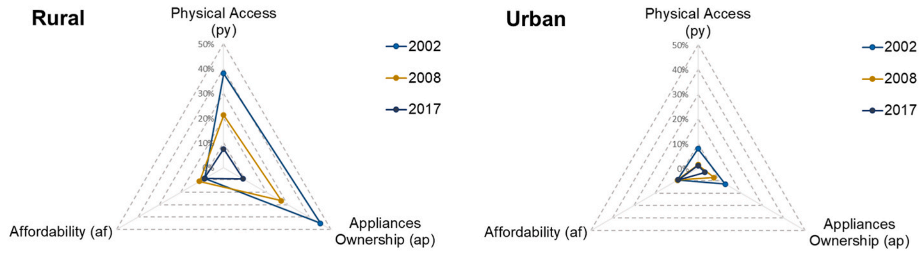

Fig. 1. Evolution of Brazilian households deprived for the period 2002–2018 in the three dimensions of energy poverty: (i) *physical access*; (ii) *appliance ownership*; and (iii) *affordability* (in %).
Note: Percentages indicate the fraction of households in a situation of deprivation, with 100% being the maximum level of deprivation.

observed across regions and income deciles.[11] From a regional perspective (Fig. 2), the North and Northeast regions started 2002 with the highest incidence of deprivation in the *physical access* and *appliance ownership* dimensions, which were significantly reduced through 2017. As a result, by 2017 the *affordability* dimension, which stayed almost constant over the years, became the largest contributor to energy poverty in those regions.

The high level of deprivation in the *physical access* and *appliance ownership* dimensions in the North and Northeast explains why in 2002–2003 these regions had the lowest deprived population in terms of the *affordability* dimension. First, a family must have *physical access* to energy in order to consume it. On the other hand, the South and Southeast regions that had the three dimensions close to the same level at the starting point were able to improve the conditions of *physical access* and *appliance ownership* but did not improve the *affordability* dimension. Since the *affordability* dimension is assessed in relative terms, it is not, like the other dimensions, very sensitive across regions and rural/urban conditions (Fig. 2). Overall, the improvements observed for the *physical access* dimension are highly associated with the decrease of biomass consumption, with the exception of the North and Midwest regions, where advances in electricity access were the main reason for the progress observed.. As for electrical connection, the remaining deprivation is concentrated in the North region, and is not significant in the other regions. More about the heterogeneity of the results can be seen in Appendix A.

Besides regional differences, income distribution has a significant influence on energy poverty conditions. In 2017–2018 for urban households, deprivation in the *physical access* and the *appliance ownership* dimensions were concentrated only in the first two deciles (Fig. 3). Regarding the *affordability* dimension, the discrepancy between the first and the tenth decile is more pronounced than in the other dimensions, especially in 2017–2018.

Our results reveal an inability of households in isolated rural areas to pay for LPG. The distribution of LPG reaches almost all municipalities, but higher prices combined with lower incomes leads to the use of firewood in these locations (Giannini Pereira et al., 2011; Mazzone et al., 2019). Although there is a cultural aspect for the continued consumption of firewood (Mazzone et al., 2021b), this result is mainly related to financial constraints (Coelho et al., 2018; de população e I. and IBGE, 2018).

For the *appliance ownership*, the difference in the deprivation rate between the first and tenth decile is not significant for 2017–2018. This is mainly due to the high presence of both TVs and refrigerators in most households. On the other hand, income influences AC ownership. In urban areas of the Northern region, where there is the higher AC adoption, 13% of first decile households own AC while in the tenth decile 85% of households have it.

Interestingly, the income heterogeneity observed in 2002–2003 and 2008–2009 for the *physical access* and *appliance ownership* dimensions were not maintained in 2017–2018. In this later period, the differences between the first and tenth decile are mostly in the *affordability* dimension. In fact, *affordability* only becomes an issue when there is no deprivation in the first two dimensions. Energy expenditure accounts for a large part of total expenses for low-income families. The wealthiest households (tenth decile) spend less than 3% of their budget on energy, even with an energy consumption 157% higher than the poorest ones (first decile). In contrast, energy expenditure of the lowest income deciles exceeds 20% of their budget. As a result, *affordability deprivation reaches* more than 30% of households in the first decile.

4.2. MEPI

By combining the energy poverty incidence (MEPI_H) and intensity (MEPI_A), we calculated the MEPI. Results show a substantial reduction in energy-poor households in all regions (Fig. 4). On average, in 2017–2018, 10.5% of households were classified as energy poor. When considering only rural homes, this percentage reaches 17%. Improvements in *physical access* and *appliance ownership* lifted 30.7% of rural households out of energy poverty between 2002 and 2017.

Following the results for each dimension, the Northern region has the highest incidence of energy-poor households, 33.7% in rural areas and 14.0% in urban areas in 2017–2018. In 2002–2003, these numbers were 77.0% and 24.6%, respectively. Results show that energy-poor households maintained the same level of deprivation over time, maintaining the same level of energy poverty intensity, from 0.337 in 2002–2003 to 0.335 in 2017–2018. In addition to having the highest incidence of energy poverty, rural areas in the Northern and Northeastern regions also have the highest values for energy poverty intensity. For the rural areas of the State of Amazonas, intensity reached 0.402 in 2017, the highest at the State level (Appendix A).

Fig. 5 maps the results for MEPI clearly showing the inequality across regions. MEPI considers both incidence and intensity, but since the latter did not change significantly over time, results mostly reflect the decrease of incidence, namely the share of households leaving the condition of energy poverty. In this sense, access to electricity in isolated areas can be considered one of the decisive factors for the improvement of MEPI in rural areas (Fig. 2).

When we observe the results by decile, the incidence of energy poverty is predominant in low-income households – Table 3. In 2017–2018, MEPI_H reached around 44% among households in the first income decile, against less than 2% in the tenth decile. The same is not observed for MEPI_A, due to the method used to calculate the intensity index – an average of the deprivation index calculated only for individuals considered energy poor.

[11] Income decile is a measurement that divides population into ten different groups, according to its income value. Each group represents ten percent of the total population considered. In that study households are stratified, with the first decile being the 10% poorest group and the tenth decile being the wealthiest households.

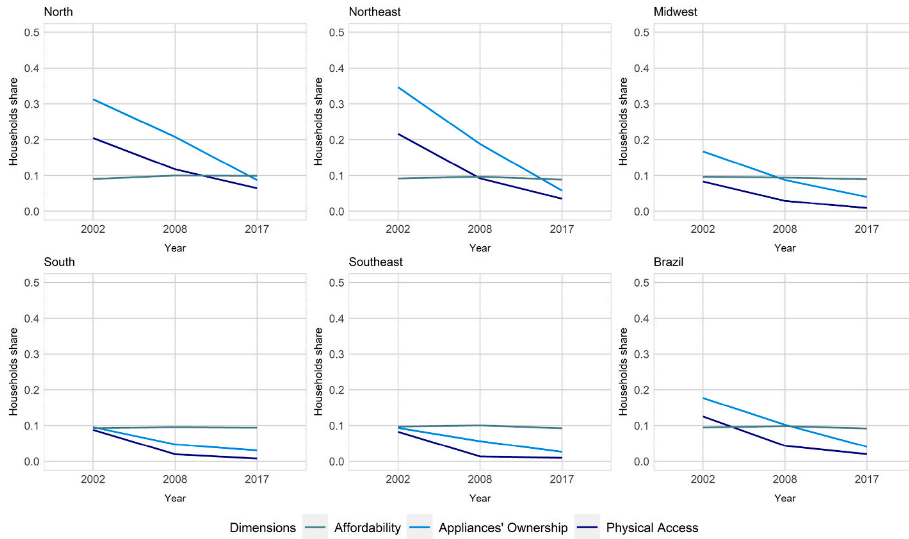

Fig. 2. Share of households in a situation of deprivation according to the three dimensions by region for the period 2002–2018 (in %).
Note: N= North, NE: North-East, MW: Midwest; S: South, SE: South-East.

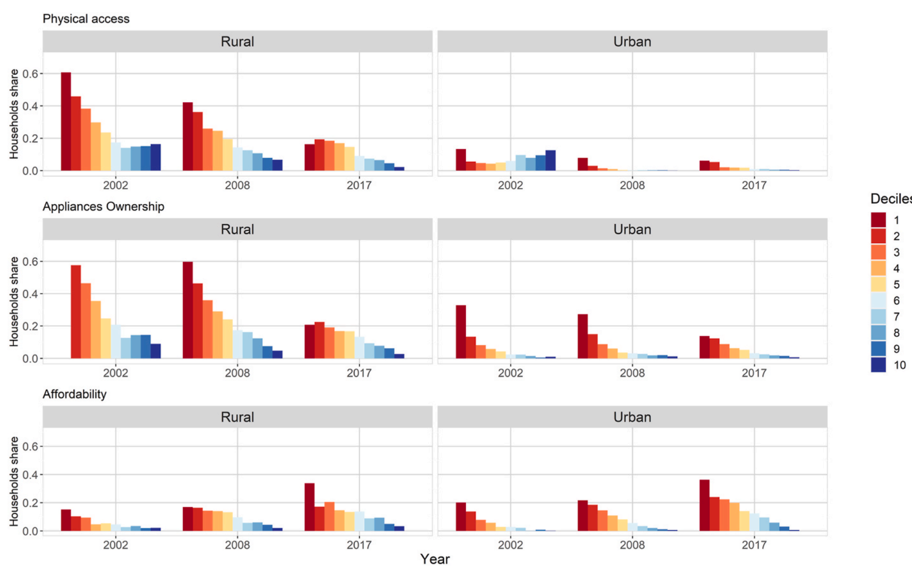

Fig. 3. Household share according to the three dimensions of energy poverty by income deciles and rural/urban situation in Brazil for the 2002–2018 period (in %).

4.3. *Sensitivity analysis*

The MEPI index is very sensitive to the choice of dimensions, their weights and cut-off values (Patrick NussbaumerMorgan et al., 2012; Pelz et al., 2018). For that, we ran some sensitivity analyses based on different cut-off values and weight composition for 2017–2018. For the cut-off, k, sensitivity values varied from $k = 0.1$to 0.9 . The higher k is, the lower the number of households defined as energy poor. For example, a value of $k = 0.5$ means that a household is defined as energy-poor when it lacks half the dimensions observed. In this study, households deprived in all dimensions can be identified when $k > 0.9$. Absolute energy poverty with deprivation across all dimensions is not commonly observed in Brazil, though there may be a deprivation of specific services. Households deprived in all dimensions are mostly found in rural areas of the States of Amazonas, Pará, Piauí, and Maranhão (Appendix A).

The number of households identified as energy poor is significantly lower, compared to the baseline $k = 0.16$, when we consider $k > 0.3$ (Fig. 6). The rural North is the only area that still has high values of energy poverty when $k = 0.5$. Poverty intensity is not as sensitive to the cut-off changes. This is because we measure MEPI_A as an average of all households with $di \geq k$. MEPI is not significant in Brazil when $k > 0.3$ for urban areas and for $k > 0.5$ in rural areas (Fig. 7).

In addition, we compute different MEPI_H values for various weight combinations. Fig. 8 shows the minimum and maximum values for energy poverty for each region. The maximum incidence of poverty occurs when $w_{py} = 0.33$, $w_{ap} = 0.5$ and $w_{af} = 0.17$, showing that access to AC appliance ownership is currently the primary service in deprivation in the country. Minimum values are found for $w_{py} = 0.64$, $w_{ap} = 0.29$ and $w_{af} = 0.07$. Results from the sensitivity analysis do not change the overall conclusions. The same inequalities are observed. Rural households located in the Northern and Northeastern regions remain with the highest values of MEPI_H, and low-income households are those most deprived in all situations.

5. Discussion

In this section, we discuss the heterogeneities of energy poverty in

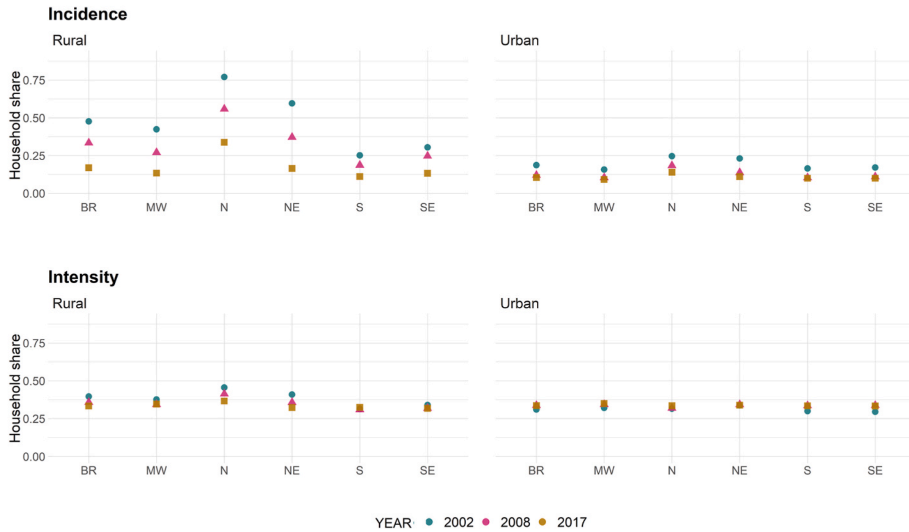

Fig. 4. Measure of incidence and intensity of energy poverty for the period 2002–2018 (range from 0 to 1).

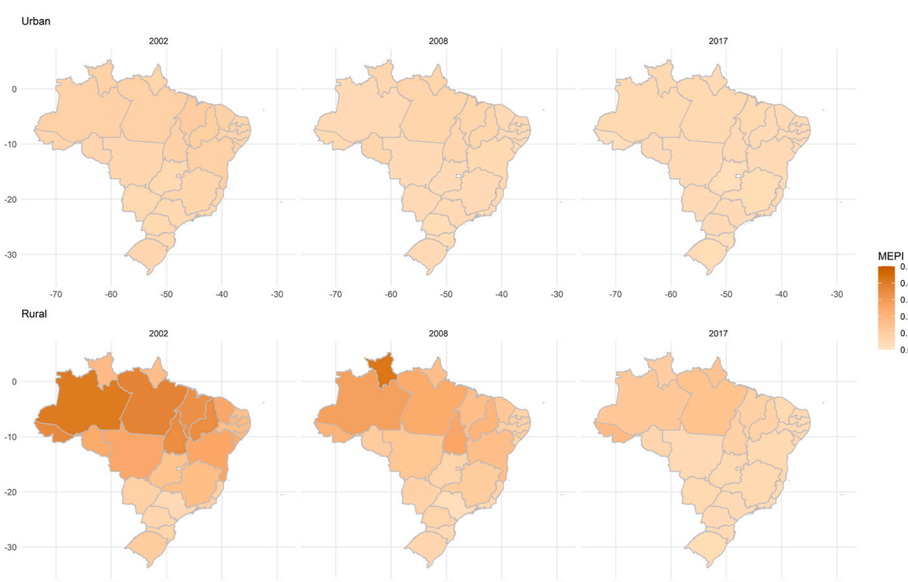

Fig. 5. Incidence and intensity of energy poverty through the MEPI index across Brazilian States for the 2002–2018 period.
Note: A higher index is associated with a situation of more severe energy poverty.

Brazil, focusing on the differences across regions and income levels. Also, to better understand the context in which energy poverty occurs, we briefly analyze the overall living conditions of those identified as energy poor.

5.1. Energy poverty and relative living and surrounding conditions

By categorizing energy poverty according to some features of households and individuals, we bring new evidence to statements made in previous studies that energy poverty is a contextual issue interlinked with other deprivation conditions. To understand how conditions of energy poverty are increasingly observed under certain circumstances, we identified the most vulnerable groups according to different infrastructural, and social characteristics, which could be very helpful for the designing and targeting of new policies.

The variables observed were chosen by taking account of the existing literature on energy poverty and minimal requirements for decent living (Rao et al., 2019a; Vine, 2020). The data from POF (IBGE) provide information about the characteristics of households and their surrounding infrastructural situation. POF data on housing conditions not only contain information on natural lighting and reduced living spaces, but also show the presence of roof leakage, humidity, and deteriorated building materials. As for the surrounding infrastructure, POF data provides information about the existence of paved streets, potable water supply and sanitation. We acknowledge the presence of other dimensions that may influence the severity and consequences of energy poverty, such as geography (Bouzarovski, 2014) and urban planning (Sánchez-Guevara Sánchez et al., 2020), but we do not deal with them here.

Previous studies highlight a correlation between living conditions and energy poverty (Sambodo and Novandra, 2019; Bhattacharya et al., 2021). The condition of a household can be related to a family's energy poverty conditions (Aristondo and Onaindia, 2018a), as it can be related to a building's energy efficiency in terms of the need to ensure indoor thermal comfort (Pérez-Fargallo et al., 2020; Gillard et al., 2017). The overall living conditions of households can be correlated with monetary conditions of poverty, which are also a cause of energy poverty (Paudel, 2021; Rao and Pachauri, 2017). Fig. 9 shows the difference in the

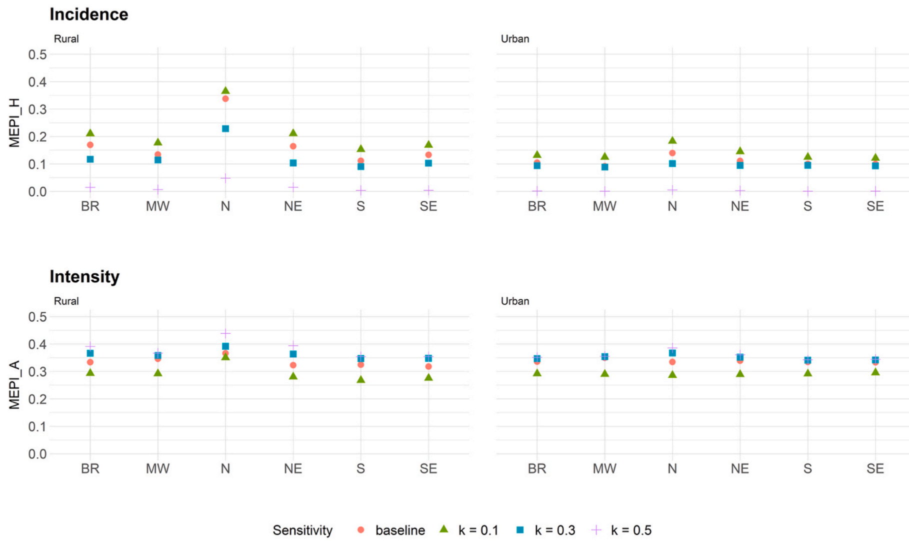

Fig. 6. Incidence (MEPI_H) and intensity (MEPI_A) of energy poverty for different cut-off (***k***) values for the 2017–2018 period.
Note: The closer ***k*** is to 1, the higher is the region's deprivation incidence or intensity.

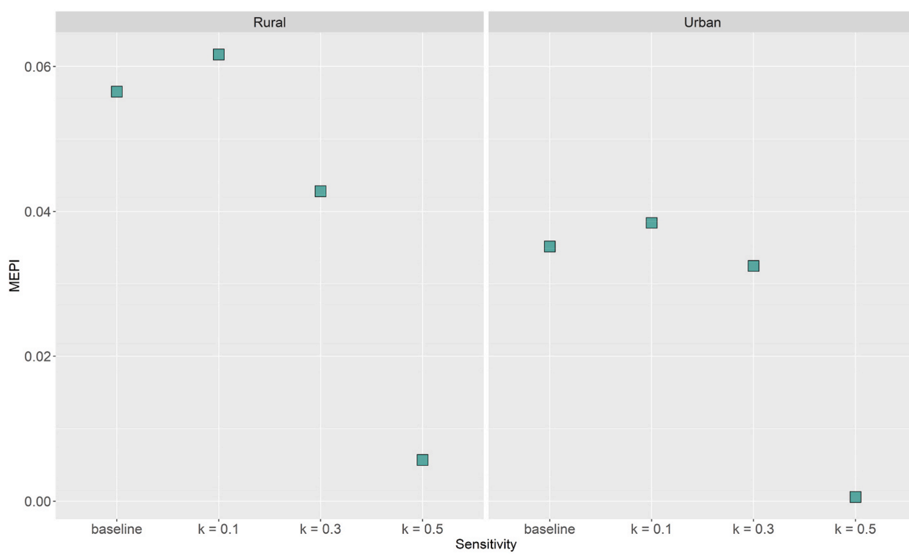

Fig. 7. MEPI values for the 2017–2018 period, for different cut-offs (***k***).
Note: The closer k is to 1, the fewer are households defined as energy poor.

prevalence of poor/limited living and surroundings conditions of energy poor and non-energy poor households, compared to Brazil's average incidence of energy poverty. Our data show that the overall living conditions of energy-poor households are significantly worse than non-poor ones, regarding both the structural condition of the home and the general situation of its surroundings. Moreover, there is a lack of public infrastructure in Brazil's rural areas. The gap between rural and urban areas regarding access to paved streets, water supply and sewage is much greater than the gap observed in other housing attributes (household conditions and infrastructure). The lack of essential infrastructure can be correlated with a higher incidence of deprivation in *physical accessibility*, while housing characteristics approximate the conditions of a family's wealth and therefore relate to *affordability* deprivation.

In Brazil, the lack of public infrastructure in rural areas is related to a broader context of geographical and economic isolation, which may be why energy poverty persists, especially in the Northern region, largely occupied by the Amazonian canopy. Massive distances and the lack of affordable public transportation between towns and villages cause price hikes for food and essential goods (including LPG) for local populations, deepening economic and social inequalities (Mazzone, 2020b). The average cost of an LPG canister (13 kg) in the State of Amazonas can be 26% higher than in the State of Rio Grande do Sul (ANP, 2022). Likewise, Amazonian citizens pay 18% more for diesel fuel compared to those living in the southern states of Rio Grande do Sul and Paraná. Future research for further understanding the effect of isolation and lack of infrastructure could assess time spent in transportation – which is potentially subtracted from other socioeconomic activities – and compare the price of goods and services across regions.

We also examine some characteristics of household heads, including gender, race, and literacy (see Table 5). Differences were mainly observed in urban areas, where energy poverty is more frequently associated with female-headed households and is most common in households with non-white and non-literate family heads. These results are not surprising, given the high incidence of gender and racial inequality in Brazil. Women and children pay the highest price for lack

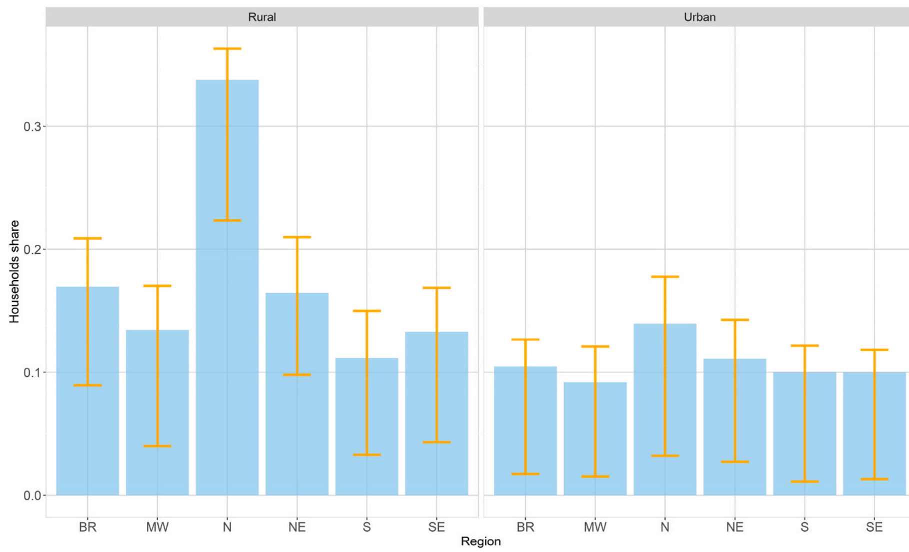

Fig. 8. Results of weight sensitivity dimensions by region for the 2017–2018 period.
Note: The distribution bar indicates the maximum and minimum values of energy poverty when varying the dimension weights.

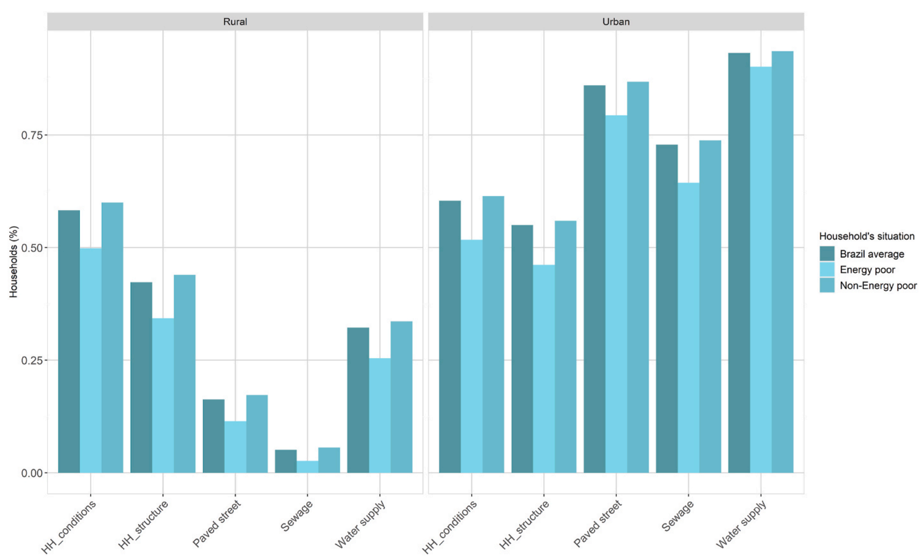

Fig. 9. Overall living conditions of households vis-à-vis their energy poverty situation (in % of households).

of public infrastructure and geographical isolation (Parikh et al., 2015; Figart and Warnecke, 2013; LeavensKennedy. and Anderson, 2011). In addition, black and mixed-race people in Brazil account for the highest percentage of the unemployed and are considered the most vulnerable in finding and keeping a job (IBGE, 2019). In 2019, before the Covid-19 pandemic, black and mixed-race Brazilians represented 64% of the unemployed and 66% of people in precarious occupations. Structural racism in Brazil impedes an equal distribution of the resources and opportunities among the population, disproportionately affecting the black, mixed-race, indigenous, and traditional populations. Racial inequalities intersect with those of gender, which are still persistent in Brazil (Pietropaoli and Xavier Baez, 2020; Simões and Matos, 2008).

Lastly, we also assessed information about the financial situation of households, in terms of average income, arrears on utility bills,[12] *BF* beneficiaries, and constraints on food purchasing.[13] Table 4 also presents disparities between energy poverty groups according to rural and urban status. The average income of households defined as energy poor is lower than the average for all Brazilian households and is markedly different from the non-poor, especially in urban areas. Energy poverty most affects BF recipients. Also, between 24% of urban families and 34% of rural families that declared food deprivation are identified as energy-poor, against 15% and 22% of non-energy poor.

The results for households that declared arrears on utility bills contrast with the other variables described above. When observing energy poverty in relation to delays in paying bills, we found that non-energy poor households are more frequently in debt than poor ones. This could indicate that people not identified as energy poor are

[12] The IBGE survey questionnaire on living conditions on the POF (2017–2018). Question: During the 12-month reference period, has your family delayed payment for water, electricity, or gas because of financial difficulties?.

[13] According to the POF (2017–2018), we considered as food deprived those households that answer *yes* on variable V6109 of the "Living Conditions" questionnaire: "In the last three months, has the food run out before the residents of this household had the money to buy more food?" (IBGE).

Table 4
Average results of MEPI and its components (MEPI_H and MEPI_A) by income decile for the 2017–2018 period (values vary from 0 to 1, 1 being the worst situation of the energy poverty index considered).

	Decile									
	1	2	3	4	5	6	7	8	9	10
MEPI_H	0.440	0.313	0.268	0.233	0.175	0.150	0.114	0.080	0.046	0.016
MEPI_A	0.356	0.349	0.343	0.339	0.333	0.337	0.330	0.332	0.318	0.307
MEPI	0.156	0.109	0.092	0.079	0.058	0.050	0.038	0.026	0.015	0.005

Table 5
Monetary conditions and characteristics of household heads according to the energy poverty situation.

Types of monetary conditions and household head characteristics		Unit	Urban/Rural	Brazilian average	Energy-poor	Non-energy poor
Monetary conditions	Average income	R$/year	Urban	68,924	28,710	73,622
			Rural	36,674	21,541	39,761
	Bolsa Família (BF)	% household	Urban	0.11	0.19	0.10
			Rural	0.32	0.40	0.30
	Arrears on utility bills	% household	Urban	0.67	0.58	0.68
			Rural	0.65	0.61	0.66
	Food restrictions	% household	Urban	0.16	0.24	0.15
			Rural	0.24	0.34	0.22
Household's head characteristics	Race (non-white declared)	% household	Urban	0.54	0.65	0.52
			Rural	0.66	0.75	0.64
	Sex (female)	% household	Urban	0.44	0.49	0.43
			Rural	0.31	0.30	0.31
	Non-literate	% household	Urban	0.13	0.22	0.12
			Rural	0.31	0.38	0.29

borderline poor in terms of their ability to afford essential energy services and, therefore, are in a situation of energy vulnerability. Moreover, late payments for services can indicate budget constraints and the likelihood of families needing to choose between energy and other goods.

5.2. Important aspects of energy poverty in Brazil

The regional disaggregation used to measure energy poverty through MEPI lines up well with the geographical heterogeneity observed for other indexes, such as the Human Development Index (HDI) and income poverty (PNUD IPEA, 2016). While the country has, on average, 11.4% of its population living in conditions of energy poverty, regional results vary from 9.7% in the Midwest to 18.5% in the North, reaching 33.8% in the rural North. *Physical access* and *appliance ownership* dimensions contributed most to this result.

MEPI also reflects social inequalities. As expected (Coelho et al., 2018; Grottera et al., 2018; Gioda, 2019b; Sanches-pereira et al., 2016), poor rural households had the highest MEPI values. Furthermore, the use of biomass for cooking is more frequently observed in the lowest income groups. The *affordability* dimension showed the largest variation among income deciles in 2017–2018. Our historical analysis shows that households need to guarantee their most basic forms of energy access before they are considered deprived in the *affordability* dimension. The first decile condition reflects this (Fig. 3). Only when there are lower levels of *physical access* and *appliance ownership* is there a high share of households with *affordability* deprivation. From this, we can conclude that Brazil is following the trend in energy policy concerns of the developed countries (Winkler et al., 2011), where energy poverty is mostly associated with constraints in paying for energy services, also called fuel insecurity (Bouzarovski and Petrova, 2015; Bouzarovski, 2014; Boardman, 1991), and not exactly due to infrastructure limitations (Guzowski et al., 2021; Lowans et al., 2021). Brazil has achieved important improvements in guaranteeing access to electricity and LPG resale infrastructure (Mazzone et al., 2019; da Silveira Bezerra et al., 2017; Grottera et al., 2018).

The persistent level of deprivation in the *affordability* dimension also suggests that, in line with previous studies (Coelho et al., 2018; Mazzone et al., 2021a), programs like BF and TSEE (Table 1) were not sufficient to ensure lower energy expenses and to lift families out of energy poverty. In addition, half of Brazilian households again declared arrears on water, electricity, or natural gas bills, especially in the Northern region, as already suggested by previous findings (Piai Paiva et al., 2019). The high share of energy expenses make households more vulnerable to energy price fluctuations and economic downturns (Pereira et al., 2021). For example, households' arrears with electric bills have increased in the last year due to the Covid-19 pandemic (Rosa, 2021; Santos et al., 2020). Moreover, there has been an increase in the use of solid fuels for cooking, even in urban areas, likely to be caused by increasing LPG prices (ANÍBAL et al., 2021). This shows that further refinements of the definition of energy poverty solely based on the *physical access* dimension could help to identify circumstantial energy poverty. The likelihood of the inability of households to pay for energy services should be considered, and fuel stacking practices should be further analyzed in future studies. Also, we should consider reliability when it comes to electricity access (Ayaburi et al., 2020). According to POF data, in the 2017–2018 period, while 1% of Brazilian households were not connected to the electricity grid, about 3% complained of supply irregularities, declaring that the service was only available for a few hours a day, or there were constant cut-offs. Problems of service quality are most frequent in the rural areas of the Northern and Midwestern regions, reaching 22% and 9% of total households. The inconstancy of electrical services is a problem for some appliances and could cause equipment damage. The incidence of energy poverty would be higher in Brazil if we accounted for the reliability of the electricity supply.

In keeping with the trend observed for the *physical access* dimension, *appliance ownership* also showed substantial growth. The access to electricity and the economic improvement of the past decades have enabled most families to purchase at least essential electrical equipment such as TVs and refrigerators, essential to improve living standards (Rao et al., 2019a). AC was the only appliances considered in this study with very limited use in the country, and significantly influenced by region and income level. The Northern and Northeastern regions showed the highest deprivation in indoor cooling parameters because of the low presence of AC and the climate conditions in those regions, which have the highest CDD_{normal} values (thermal comfort parameter). As for

Brazil's climate change scenarios, space cooling technologies will be an important asset for enhancing well-being (Mastrucci et al., 2019; Bezerra et al., 2021; EPE [Empresa de Pesquisa Energética], 2018). Hence, future studies should focus on the thermal comfort parameter and the role that AC ownership plays in energy poverty metrics. The same is valid for internet access, which plays an important role in education (UNESCO, 2003), especially after the Covid-19 pandemic. Although the internet depends on the telecommunication infrastructure, it can also be regarded as an energy service.

6. Conclusion and policy implications

The ability to evaluate energy poverty over time is key to the design of effective policies (Alem and Demeke, 2020; Aristondo and Onaindia, 2018b). For large countries, a broader analysis requires the characterization of energy poverty understanding its geographical distribution (Gouveia et al., 2019). Since Brazil particularly has a vast territory and a large gap between living conditions in urban and rural areas (de população e I. and IBGE, 2018), any historical analysis of energy poverty must comprehend its heterogeneous conditions.

This paper analyzes the energy poverty incidence and intensity in Brazil and its geographical regions for three different periods, 2002–2003, 2008–2009, and 2017–2018. We incorporate the concept of energy deprivation according to the final service demanded, using a Multi-dimensional Energy Poverty Index (MEPI). The paper furthered the definition of energy poverty in a broader sense, by using a quantitative approach to measure energy service through dimension deprivation by its different economic and regional characteristics. The focus on those dimensions allowed us to gain a deep understanding of how the definition of energy poverty can be contextual, and thus to add an important insight to the energy poverty literature.

Overall, MEPI has detected significant improvements in Brazil in the periods observed. However, despite these improvements, 11% of Brazil's population currently lives in conditions of energy poverty. In urban areas, this is due mainly to affordability issues, while in rural areas – where 16% of all households are still considered energy poor– all dimensions contribute to the results observed. The reduction in energy poverty was not as marked as the improvements in its intensity, in the sense that energy-poor households remained just as deprived in the 2017–2018 period as they were in the 2002–2003 period.

In addition, by quantifying energy poverty through time by geographic area and the urbanization level, the paper has demonstrated the relevance of understanding energy poverty considering its local context. Households on rural areas of North and Northeast regions were most likely to living in energy poverty conditions than those in urban areas of South or Southeast. Also, energy poverty is most likely observed on households with low-income levels and living with limited surrounding conditions and with certain social characteristics of the head of the family. Considering the above-discussed two main finds can be explored to help to design policies to eradicate energy poverty in Brazil.

First, we suggest that current governments should consider making further adjustments to their programs to reduce energy poverty, focusing on its *affordability* dimension. Specifically, we show that *physical access* to energy was insufficient for reducing the deprivation of essential energy services. Energy expenditure still represents a high share of the total expenses of low-income households. The inability to pay for energy or buy new and efficient appliances can force families to use traditional energy for cooking or not meeting thermal comfort needs. Governmental efforts such as BF and TSEE did not provide sufficient means to change the energy expenditure to total income ratio of low-income households, which remained almost constant over time. Also, it is shown that low energy poor conditions are most observed in families on the first- and second-income deciles, as in those with declared income constrains. For that, we would suggest that policy measures could considered the use of progressive tariffs. The use of such has been showed beneficial on other countries (Dehmel, 2011; So, 2017).

Second, in order to design policies for eliminating energy poverty it is important to identify energy-poor clusters of the population through context-specific and comprehensive metrics (Pachauri and Spreng, 2011; Patrick NussbaumerMorgan et al., 2012). Heterogeneity in the use of energy services has been demonstrated in this work, and people who suffer from energy deprivation are more likely to suffer other disadvantages too. The study shows that households in poor neighborhoods with lack of other essential services, as potable water, are more likely to be energy poor. Efforts to strengthen infrastructure, combined with energy affordability programs, would have a better chance of reducing structurally energy poverty in deprived areas. This could be the case of rural areas from the North region.

Although the results demonstrated, MEPI can be limited with regard to their chosen dimensions and their weighting (Day et al., 2016; Patrick NussbaumerMorgan and Yumkella, 2011; Pelz et al., 2018). Since our main goal is to evaluate energy poverty over time, we opted to focus our analysis on the dimensions that are most used in the literature (Pelz et al., 2018). For that reason, this work could not observe all energy services related with home needs and some productivity and community energy use as one of its MEPI dimensions. Therefore, future studies should consider more forms of energy services for its dimensions. When observing some specific income groups, countries and regions (Kaygusuz, 2011; Pachauri and Rao, 2020), including the rural areas of Brazil (Mazzone, 2020a; da Silveira Bezerra et al., 2017), productivity and community energy use is of extreme relevance.

Regarding dimension's weights, we opt to use the equal weighting; in which all dimensions are equally important, implying in a substitutability condition (Decancq and Lugo, 2008). This trade-off characteristics can well describe time evolution of multidimensional indexes (Santos, 2019), as done in this paper, but is limited to point out the relative importance of each dimension chosen (Santos, 2019; Decancq and Lugo, 2008). The work explores this limitation as a sensitive case and concluded that there is no difference in terms of its main finds. Other schemes of weighting, as statistical or frequency-based weights, could be explored to identify the relative importance of the dimensions chosen in the different regions of Brazil, implying in a more focused policy-oriented work (Decancq and Lugo, 2008).

The cut-off also can be a limitation of MEPI, as it reflects a judgement of the minimum acceptance of deprivation conditions (Santos, 2019). When we use $k > 0.16$, we gave a higher relative importance for the parameters in the *physical access* dimension and a smaller for *appliance ownership*'s parameters. For example, a household that owns TV and refrigerator but do not possess AC is not considered energy poor. For future studies, some could choose a smaller cut-off to give AC its relative importance. This could be of extreme importance in Brazilian hot weather regions and for climate change scenarios.

Moreover, it is important to understand the determinants of energy poverty in order to design more effective policy initiatives (Meyer et al., 2018; Ye and Koch, 2021; Oswald et al., 2021). This study has identified which groups are most affected by conditions of energy poverty. This aspect should be better explored in future studies in order to achieve a more comprehensive analysis of the relationships between energy poverty and social/geographical determinants. Also, for future studies our results can offer advice on how to improve the MEPI methodology by focusing more on specific locations and groups (Karpinska and Śmiech, 2020). Some important aspects of energy poverty that may be relevant for rural areas have not been considered in this paper, such as those related to availability and reliability of energy access (Pereira et al., 2021; Mazzone et al., 2021b; Urquiza et al., 2019).

Bearing in mind the limitations of the methodology, we were nevertheless able to judiciously apply MEPI to make a historical evaluation of energy poverty by exploring how the deprivation of energy services has changed over time across different regions and income deciles. Our study delivers some important finds, and by making necessary adjustments for local characteristics, the methodology can be extended to neighboring countries.

CRediT authorship contribution statement

Paula Bezerra: Lead and corresponding author. Conceptualization, Methodology, Data curation, Writing – original draft, Writing – review & editing, Dr. **Talita Cruz:** main co-author. Support on conceptualization, Data curation, Writing – original draft, Writing – review & editing. **Antonella Mazzone:** Support on conceptualization, Writing – original draft, Writing – review & editing, Validation. **André F.P. Lucena:** Support on conceptualization, Supervision, Writing – review & editing, Resources, Validation. **Enrica De Cian:** Data curation, Supervision, Writing – review & editing, Resources, Validation. **Roberto Schaeffer:** Supervision, Writing – review & editing, Resources, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. See Table A1-Table A4 and Figure A1

Table A1
Different weights for the dimensions selected, based on the rank exponent method

Dimension	ρ	rank		rank		rank		rank		rank		rank	
Physical access	0	phy = 1; ap = 3; exp = 2	0.333	phy = 1; ap = 2; exp = 3	0.333	phy = 2; ap = 1; exp = 3	0.333	phy = 2; ap = 3; exp = 1	0.333	phy = 3; ap = 1; exp = 2	0.333	phy = 3; ap = 2; exp = 1	0.333
	0.5		0.418		0.418		0.341		0.341		0.241		0.241
	1		0.500		0.500		0.333		0.333		0.167		0.167
	1.5		0.576		0.576		0.313		0.313		0.111		0.111
	2		0.643		0.643		0.286		0.286		0.071		0.071
Appliance ownership	0		0.333		0.333		0.333		0.333		0.333		0.333
	0.5		0.241		0.341		0.418		0.241		0.418		0.341
	1		0.167		0.333		0.500		0.167		0.500		0.333
	1.5		0.111		0.313		0.576		0.111		0.576		0.313
	2		0.071		0.286		0.643		0.071		0.643		0.286
Affordability	0		0.333		0.333		0.333		0.333		0.333		0.333
	0.5		0.341		0.241		0.241		0.418		0.341		0.418
	1		0.333		0.167		0.167		0.500		0.333		0.500
	1.5		0.313		0.111		0.111		0.576		0.313		0.576
	2		0.286		0.071		0.071		0.643		0.286		0.643

Table A2
Energy expenses and its share of a household's total expenditure

	Rural					
	Brazil	North	Northeast	South	Southeast	Midwest
2002	501.00 (8.8%)	411.14 (9.3%)	376.51 (8.5%)	698.21 (8.4%)	603.55 (9.3%)	600.24 (9.8%)
2008	552.30 (11.3%)	497.15 (12.4%)	388.01 (10.6%)	823.72 (11.2%)	708.44 (12.1%)	732.46 (11.9%)
2017	1402.05 (9.0%)	1133.56 (10.6%)	1144.98 (8.1%)	2020.31 (9.0%)	1638.64 (9.9%)	1721.70 (10.4%)
	Urban					
	Brazil	North	Northeast	South	Southeast	Midwest
2002	795.17 (9.6%)	768.68 (8.9%)	576.22 (8.5%)	867.71 (9.5%)	872.21 (9.8%)	800.87 (9.7%)
2008	1047.16 (9.6%)	1000.87 (9.2%)	781.21 (10.6%)	1097.39 (9.3%)	1157.56 (9.9%)	1072.79 (9.0%)
2017	1962.75 (9.2%)	2272.38 (9.7%)	1606.71 (8.1%)	2047.30 (9.5%)	2023.80 (9.2%)	2227.77 (8.8%)

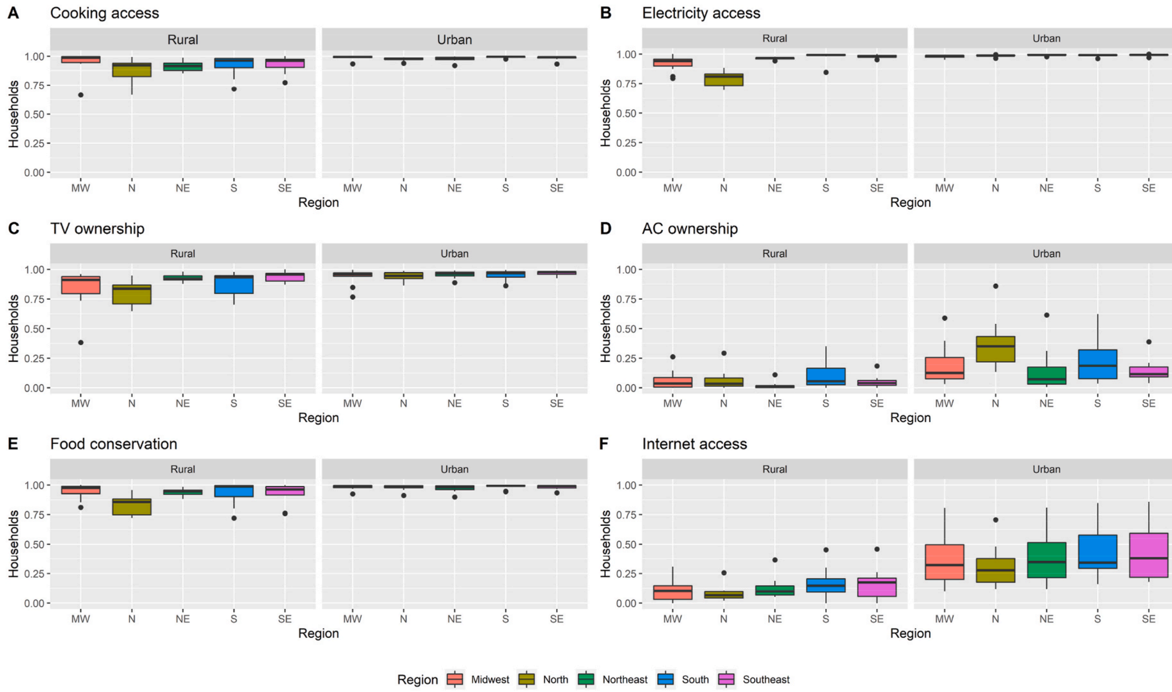

Fig. A1. Heterogeneity of Brazil's appliance ownership

Table A3
Dimensions and MEPI results by State and rural/urban situation

State	HH situation	py_H	ap_H	af_H	MEPI_H	MEPI_A	MEPI
AC	rural	0.36	0.35	0.11	0.45	0.28	0.13
	urban	0.01	0.06	0.07	0.08	0.19	0.02
AL	rural	0.03	0.09	0.08	0.13	0.08	0.01
	urban	0.01	0.05	0.08	0.10	0.07	0.01
AM	rural	0.20	0.25	0.10	0.28	0.38	0.11
	urban	0.03	0.05	0.10	0.14	0.18	0.03
AP	rural	0.28	0.18	0.11	0.39	0.65	0.25
	urban	0.01	0.03	0.07	0.10	0.40	0.04
BA	rural	0.08	0.10	0.07	0.15	0.05	0.01
	urban	0.01	0.05	0.10	0.11	0.06	0.01
CE	rural	0.09	0.04	0.07	0.17	0.13	0.02
	urban	0.03	0.05	0.08	0.11	0.13	0.01
DF	rural	0.01	0.07	0.11	0.12	0.00	0.00
ES	rural	0.00	0.03	0.09	0.10	0.06	0.01
	urban	0.01	0.02	0.10	0.10	0.08	0.01
GO	rural	0.03	0.06	0.11	0.14	0.12	0.02
	urban	0.00	0.03	0.08	0.09	0.07	0.01
MA	rural	0.13	0.12	0.11	0.23	0.41	0.09
	urban	0.03	0.06	0.10	0.13	0.39	0.05
MG	rural	0.06	0.06	0.09	0.15	0.04	0.01
	urban	0.01	0.03	0.08	0.09	0.04	0.00
MS	rural	0.03	0.04	0.11	0.14	0.15	0.02
	urban	0.01	0.04	0.09	0.10	0.11	0.01
MT	rural	0.03	0.08	0.09	0.13	0.03	0.00
	urban	0.02	0.04	0.09	0.10	0.02	0.00
PA	rural	0.24	0.24	0.10	0.40	0.57	0.23
	urban	0.02	0.04	0.10	0.15	0.49	0.08
PB	rural	0.04	0.07	0.09	0.12	0.08	0.01
	urban	0.01	0.05	0.10	0.11	0.07	0.01
PE	rural	0.06	0.09	0.08	0.14	0.04	0.01
	urban	0.02	0.04	0.10	0.12	0.08	0.01
PI	rural	0.12	0.13	0.07	0.20	0.23	0.05
	urban	0.02	0.04	0.08	0.10	0.21	0.02
PR	rural	0.02	0.07	0.10	0.12	0.02	0.00
	urban	0.01	0.05	0.11	0.11	0.01	0.00
RJ	rural	0.02	0.05	0.10	0.12	0.05	0.01
	urban	0.01	0.02	0.09	0.10	0.02	0.00
RN	rural	0.07	0.03	0.07	0.13	0.18	0.02
	urban	0.02	0.03	0.08	0.10	0.15	0.02

(continued on next page)

Table A3 (*continued*)

State	HH situation	py_H	ap_H	af_H	MEPI_H	MEPI_A	MEPI
RO	rural	0.03	0.08	0.13	0.16	0.26	0.04
	urban	0.02	0.06	0.10	0.12	0.20	0.02
RR	rural	0.14	0.14	0.09	0.23	0.35	0.08
	urban	0.03	0.07	0.08	0.16	0.25	0.04
RS	rural	0.02	0.05	0.08	0.10	0.03	0.00
	urban	0.01	0.01	0.09	0.10	0.02	0.00
SC	rural	0.03	0.04	0.10	0.12	0.02	0.00
	urban	0.01	0.02	0.08	0.09	0.02	0.00
SE	rural	0.05	0.11	0.14	0.19	0.10	0.02
	urban	0.01	0.03	0.09	0.11	0.12	0.01
SP	rural	0.01	0.05	0.11	0.12	0.05	0.01
	urban	0.01	0.02	0.09	0.10	0.03	0.00
TO	rural	0.11	0.13	0.10	0.21	0.37	0.08
	urban	0.06	0.06	0.09	0.13	0.30	0.04

Table A4

a) Incidence of energy-poverty for different deprivation cut-off sensitivity in rural areas

	Deprivation cut-off (k)									
State	Baseline	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Acre	0.4457	0.4872	0.4457	0.3797	0.2234	0.0635	0.0245	0.0082	–	–
Alagoas	0.1305	0.1736	0.1100	0.0849	0.0310	0.0144	–	–	–	–
Amazonas	0.2812	0.3857	0.2812	0.2146	0.0920	0.0556	0.0425	0.0221	0.0041	0.0041
Amapá	0.3907	0.3922	0.3486	0.2429	0.1325	0.0649	0.0011	–	–	–
Bahia	0.1530	0.2015	0.1147	0.0872	0.0180	0.0116	0.0021	–	–	–
Ceará	0.1668	0.1986	0.0885	0.0826	0.0119	0.0045	–	–	–	–
Distrito Federal	0.1189	0.1779	0.1132	0.1063	0.0089	–	–	–	–	–
Espírito Santo	0.0961	0.1140	0.0961	0.0961	0.0152	–	–	–	–	–
Goiás	0.1429	0.1700	0.1376	0.1254	0.0234	0.0104	0.0017	0.0017	–	–
Goiás	0.0852	0.1122	0.0852	0.0852	0.0109	–	–	–	–	–
Maranhão	0.2280	0.2901	0.2280	0.1619	0.0464	0.0309	0.0190	0.0038	0.0019	0.0019
Maranhão	0.1255	0.1648	0.1255	0.1060	0.0161	0.0067	0.0032	0.0013	–	–
Minas Gerais	0.1528	0.1878	0.1121	0.1003	0.0141	0.0084	–	–	–	–
Mato Grosso do Sul	0.1392	0.1770	0.1280	0.1224	0.0107	0.0015	–	–	–	–
Mato Grosso	0.1262	0.1852	0.1132	0.0996	0.0167	0.0058	0.0005	0.0005	0.0005	–
Pará	0.3959	0.3959	0.3299	0.2448	0.1815	0.0581	0.0320	0.0054	0.0015	0.0006
Paraíba	0.1162	0.1632	0.0958	0.0891	0.0132	0.0083	0.0060	0.0051	–	–
Pernambuco	0.1398	0.1936	0.1063	0.0912	0.0207	0.0116	0.0005	–	–	–
Piauí	0.2026	0.2384	0.1603	0.1394	0.0641	0.0375	0.0022	0.0022	0.0009	0.0009
Paraná	0.1200	0.1676	0.1095	0.0957	0.0143	0.0053	0.0020	0.0012	–	–
Rio de Janeiro	0.1226	0.1561	0.1083	0.1035	0.0127	–	–	–	–	–
Rio Grande do Norte	0.1319	0.1431	0.0845	0.0717	0.0129	0.0046	–	–	–	–
Rondônia	0.1640	0.2333	0.1640	0.1399	0.0108	–	–	–	–	–
Roraima	0.2333	0.2354	0.2333	0.2176	0.0947	0.0020	0.0020	–	–	–
Rio Grande do Sul	0.0979	0.1378	0.0853	0.0802	0.0117	0.0027	–	–	–	–
Santa Catarina	0.1200	0.1565	0.0998	0.0977	0.0063	0.0031	–	–	–	–
Sergipe	0.1896	0.2578	0.1674	0.1456	0.0287	0.0105	–	–	–	–
São Paulo	0.1183	0.1608	0.1128	0.1082	0.0024	–	–	–	–	–
Tocantins	0.2110	0.2595	0.2110	0.1755	0.0681	0.0305	0.0276	–	–	–

Table A4b

b) Incidence of energy-poverty for different deprivation cut-off sensitivity in urban areas

	Deprivation cut-off (k)									
State	Baseline	0.100	0.200	0.300	0.400	0.500	0.600	0.700	0.800	0.900
Acre	0.0797	0.1365	0.0750	0.0710	0.0072	0.0012	0.0012	–	–	–
Alagoas	0.1003	0.1354	0.0940	0.0863	0.0090	0.0021	0.0005	0.0005	–	–
Amazonas	0.1438	0.1997	0.1196	0.1066	0.0261	0.0044	0.0017	–	–	–
Amapá	0.1007	0.3521	0.1007	0.0778	0.0280	–	–	–	–	–
Bahia	0.1107	0.1519	0.1047	0.0988	0.0056	0.0033	0.0005	–	–	–
Ceará	0.1089	0.1416	0.0944	0.0833	0.0101	0.0029	0.0010	0.0003	–	–
Espírito Santo	0.1039	0.1223	0.0993	0.0967	0.0050	0.0011	–	–	–	–
Goiás	0.0852	0.1122	0.0852	0.0852	0.0109	–	–	–	–	–
Maranhão	0.1255	0.1648	0.1255	0.1060	0.0161	0.0067	0.0032	0.0013	–	–
Minas Gerais	0.0933	0.1180	0.0876	0.0847	0.0055	0.0014	0.0008	–	–	–
Mato Grosso do Sul	0.0962	0.1331	0.0953	0.0923	0.0095	0.0007	–	–	–	–
Mato Grosso	0.1002	0.1419	0.0937	0.0913	0.0081	0.0022	–	–	–	–
Pará	0.1538	0.1567	0.1164	0.1052	0.0895	0.0071	–	–	–	–

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Table A4b (*continued*)

State	Deprivation cut-off (k) Baseline	0.100	0.200	0.300	0.400	0.500	0.600	0.700	0.800	0.900
Paraíba	0.1090	0.1451	0.1056	0.0976	0.0077	0.0027	–	–	–	–
Pernambuco	0.1157	0.1451	0.1036	0.0971	0.0083	0.0015	0.0005	–	–	–
Piauí	0.0963	0.1259	0.0882	0.0869	0.0102	0.0022	–	–	–	–
Paraná	0.1135	0.1528	0.1105	0.1088	0.0087	0.0006	0.0002	–	–	–
Rio de Janeiro	0.1042	0.1276	0.0986	0.0942	0.0034	0.0020	–	–	–	–
Rio Grande do Norte	0.1042	0.1318	0.0910	0.0863	0.0038	0.0014	–	–	–	–
Rondônia	0.1168	0.2119	0.1142	0.1026	0.0084	0.0017	–	–	–	–
Roraima	0.1558	0.1734	0.1083	0.0883	0.0380	0.0090	0.0028	–	–	–
Rio Grande do Sul	0.0953	0.1092	0.0904	0.0894	0.0014	0.0004	0.0004	0.0004	0.0004	–
Santa Catarina	0.0851	0.1035	0.0817	0.0803	0.0036	0.0006	–	–	–	–
Sergipe	0.1055	0.1197	0.1007	0.0933	0.0057	0.0019	0.0005	–	–	–
São Paulo	0.1011	0.1200	0.0967	0.0951	0.0042	0.0007	–	–	–	–
Tocantins	0.1329	0.1865	0.1265	0.0958	0.0138	0.0038	–	–	–	–

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