CHARACTERIZING ENERGY-POVERTY-CLIMATE NEXUS IN BRAZIL: HISTORICAL CONTEXT AND FUTURE RISKS

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"It takes a village to raise a child"

Provérbio africano

Aos meus filhos Henrique e Felipe

À minha avó Gilda

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CARACTERIZAÇÃO DO NEXO ENERGIA-POBREZA-CLIMA NO BRASIL: CONTEXTO HISTÓRICO E RISCOS FUTUROS

Paula Borges da Silveira Bezerra

Outubro/2021

Orientador: André Frossard Pereira de Lucena

Programa: Planejamento Energético

O uso de fontes modernas de energia pelas famílias está associado a diversos benefícios sociais e a diversas uso energéticos relacionadas à estas fontes. Porém, este acesso e seus benefícios ainda não são desfrutados por toda população brasileira. Uma das recentes preocupações sobre o uso elétrico nas residências é com o uso de equipamentos para conforto térmico. O calor extremo está relacionado a diversos problemas de saúde, e as mudanças climáticas tendem a intensificar este calor no Brasil. Desta forma, a partir do desenvolvimento de três trabalhos independentes, esta tese tem como objetivo discutir a relação entre acesso à energia, pobreza e desenvolvimento social e clima. O primeiro trabalho apresentado relaciona o acesso à energia elétrica em comunidades rurais com o índice de desenvolvimento sustentável (IDH). No segundo trabalho a pobreza energética é mensurada no Brasil, de acordo com uma métrica multidimensional. Já o terceiro trabalho apresenta os impactos no consumo elétrico das residências, *ceteris paribus*, em um contexto de cenários de mudanças climáticas. A partir destas três análises foi possível observar que ainda existem muitas famílias em situação de pobreza energética no Brasil, especialmente na região Norte. Esta situação pode se agravar ainda mais no contexto das mudanças climáticas.

Abstract of Thesis presented to COPPE/UFRJ as a partial fulfillment of the requirements for the degree of Doctor of Science (D.Sc.)

CHARACTERIZING ENERGY-POVERTY-CLIMATE NEXUS IN BRAZIL: HISTORICAL CONTEXT AND FUTURE RISKS

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The use of modern energy sources by families is associated with several social benefits and several uses related to these sources. However, this access and its benefits are not yet enjoyed by the entire Brazilian population. One of the recent concerns about electrical use in homes is the use of equipment for thermal comfort. Extreme heat is related to several health problems, and climate change tends to intensify this heat in Brazil. Thus, from the development of three independent works, this thesis aims to discuss the relationship between access to energy, poverty and social development and climate. The first work presented relates access to electricity in rural communities with the sustainable development index (HDI). In the second study, energy poverty is measured in Brazil according to a multidimensional metric. The third paper presents the impacts on the electrical consumption at households, *ceteris paribus*, in a context of climate change scenarios. From these three analyses it was possible to observe that there are still many families in energy poverty in Brazil, especially in the North region. This situation could get even worse in the context of climate change.

SUMMARY

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1 INTRODUCTION

Poverty is a global issue that persists nowadays. Considering the international poverty line of US$ 1.90 PPP, 9.3% of the population, or 696 million people, were considered poor in 2017 (Vine, 2020). The monetary index has been historically used to show who are deprived according to income level, reflecting the inability to pay for goods and services (World Bank, 2018). But poverty implies an overall condition of hardship that limits the choices for different alternatives of being and doing, including education, health, information, social connections, and others. Seen as the capabilities approach (Nussbaum and Sen, 1993), this perspective inspired other ways of understanding poverty and development beyond the economic-related metric.

United Nations adopts the Human Development Index (HDI) to measure development combined with the Human Poverty Index or, more recently, Global Multidimensional Poverty Index (Global MPI) as a metric of poverty (World Bank, 2018; UNDP, 2020, 2021a). The World Bank also included different poverty indexes on its recent Multidimensional Poverty Measure (MPM). According to this new definition, poverty has increased by around 50%, achieving 1.3 billion people (World Bank, 2018; UNDP, 2020).

Improving living conditions do not depend on income alone. To guarantee some essential services and needs, good monetary conditions should be combined with infrastructure (Cook, 2011; Rao and Pachauri, 2017). three dimensions build Global MPI: education, health, and standard of living. Standard of living considers aspects as sanitization, cooking fuels used, access to electricity and drinking water (UNDP, 2020), and is aligned with Sustainable Development Goals (SDG) challenges.

In September 2015, all 193 United Nations member states adopted the 2030 Agenda for Sustainable Development with its 17 SDGs (UNDP, 2021b), calling for the eradication of poverty in all its forms and dimensions:

> *"We recognize that eradicating poverty in all its forms and dimensions, including extreme poverty, is the greatest global challenge and an indispensable requirement for sustainable development.*

The 17 Sustainable Development Goals and 169 targets…. are integrated and indivisible and balance the three dimensions of sustainable development: the economic, social and environmental." (UNDP, 2021, p.5)

Energy access is one of the SDGs (SDG 7 – Clean and Affordable Energy). It is considered on the Global MPI and is assumed to be essential to eradicate poverty and achieve sustainable development (Modi *et al.*, 2005; GNESD, 2007). Modern fuels are related to several benefits for the population, at the individual level, and for the community (World Bank & ESMAP, 2015).

Energy is considered an important ally to improving education, health, productivity, gender equality, and environmental goals (GNESD, 2007). Shifting to clean cooking fuels reduces the exposure of inhaling noxious smoke that causes respiratory illness (Gioda et al., 2019; WHO, 2014). Also, diminishing the process of collecting firewood liberates time for education and productive activities, impacting mainly the life of children and women (Modi *et al.*, 2005; Mazzone, Cruz and Bezerra, 2021). Educational gains are also observed in electrified regions. Electricity access enables night study and allows the use of communication and information appliances (MDA Pesquisas, 2013b). Furthermore, electricity enables the use of different appliances necessary for public activities such as water treatment and supply, hospital facilities, and others (SE4All, 2019; World Bank & ESMAP, 2015).

From a household perspective, the concept of energy poverty is critical for understanding which measures can be prioritized to attain higher welfare levels (Khandker, Barnes and Samad, 2012). To understand the impact of energy on socioeconomic development and welfare in all its depth, it is necessary to have a clear definition and simple metrics. Energy poverty goes beyond the lack of physical access; It is caused by a complex combination of factors and should be described to point out those dynamics (Pachauri and Spreng, 2011). To capture all aspects related to energy poverty conditions, multidimensional indexes have been recently proposed (Pachauri & Rao, 2020; Patrick Nussbaumer, Morgan Bazilian, et al., 2012; World Bank & ESMAP, 2015). Such indexes intend to overcome the restricted definition of fuel poverty based mainly on the affordability approach, where a household is considered to be energy poor if it spends above a defined threshold of its income on energy (Patrick Nussbaumer, Morgan Bazilian *et al.*, 2012; Ochoa and Ed, 2016).

Multidimensional indexes rate energy according to its final energy services and ultimately to the capabilities associated with them, as physical health, well-being, quality of life, living conditions, and so on (Day, Walker and Simcock, 2016; Audrey Berry, 2018). From this perspective, each dimension corresponds to the use of energy to meet the basic energy needs for lighting, cooking, food conservation, indoor thermal comfort, and others (González-Eguino, 2015).

The dimension of thermal comfort, mostly limited to indoor heating, has often been observed in studies about fuel poverty (Fabbri, 2015, 2019; Mould and Baker, 2017; Baker, Mould and Restrick, 2018). But now, concerns about proper indoor heating have been combined with proper indoor cooling, more often needed due to the warmer conditions observed (Horta *et al.*, 2019; Papada and Kaliampakos, 2019; Thomson *et al.*, 2019). Some studies outlined the term energy vulnerability to understand the risks of climate change on household's conditions of energy poverty.

Global warming could induce higher demand for ambient cooling, increasing energy needs and electricity expenditure associated with it (Depaula and Mendelsohn, 2010; Davis and Gertler, 2015; Dirks *et al.*, 2015). This could lead households to spend a larger share of their income on electricity, affecting disproportionally low income families (Randazzo, De Cian and Mistry, 2020). The problem is even more alarming in Global South. As pointed out by Mastrucci et al., (2019) raising temperatures associated with the lack of indoor colling can be seen as a dimension of energy poverty and human wellbeing. When considering the needs for space cooling, the energy poverty measure is higher than those solely based on an access metric (Mastrucci *et al.*, 2019a).

The capacity to adapt to climate change of those living in poverty is limited, and the needs for thermal comfort, the possibility of rebuilding after extreme events or to migrate are restricted (Triana, Lamberts and Sassi, 2018; Vine, 2020). Climate change could increase the price of food and energy, impacting energy affordability and increasing energy poverty (Fuso Nerini *et al.*, 2019), making it harder to eradicate poverty and hunger in the world. Climate change can have implications on 72 SDG targets, affecting the achievability of those goals (Fuso Nerini *et al.*, 2019). Moreover, mitigation policies may well impact populations disproportionally, being harder on the poor (Soergel *et al.*, 2020).

A clear example of the impact of climate change on the vulnerability of the poorest can be observed in rural areas, where multidimensional poverty is more commonly observed

(Vine, 2020). The lack of access to electricity and high use of biomass for cooking – two key indicators of energy poverty – are concentrated on rural Global South region (Pereira, Freitas and da Silva, 2010; Kaygusuz, 2011; Khandker, Barnes and Samad, 2012). The situation in such areas may significantly worsen in the future. The rural activities are the most vulnerable to climate change consequences, such as environmental shocks and climate-related extreme events (Bouzarovski, Petrova and Tirado-Herrero, 2014; Hallegatte and Rozenberg, 2017). Overall, climate change is a challenge to be overcome by the society, since its consequences can dramatically increase the number of vulnerable situations to which poor people can be exposed, and may even reverse trends in poverty reduction (Leichenko and Silva, 2014; Mathy and Blanchard, 2016)

In Brazil, the frequency of extreme events associated with hotter weather conditions increased in the last decades (Ministério de Ciência e Tecnologia, 2020). In addition to this climate vulnerability, Brazil historically faces poor social conditions suffered by part of its population. About 24.7 million Brazilians lived in poverty income conditions in 2019, and 6.5 million people in extreme poverty (IBGE, 2018). This numbers are even higher considering the multidimensional Global MPI (UNDP, 2020).

The major program to eradicate poverty in Brazil was *Bolsa Família* (BF). Launched in 2003, BF is a cash transfer program that currently attends 13.9 million families (Caixa Economica Federal, 2021). Based on the idea of multidimensional poverty, the program merged different previous policies of social assistance, reducing inefficiencies and ensuring the access to other social benefits (IPEA and WWP, 2014). One of the programs merged with BF was *Auxílio-Gás*, from which families periodically received a voucher to purchase Liquefied Petroleum Gas (LPG) for cooking.

Other program, *Luz para Todos (LpT)*, launched in 2003 in Brazil, also embodied the multidimensional perspective of energy and poverty, recognizing electricity access as a way to promote social and economic development and to reduce social inequality in rural communities.

Despite the success of programs like LpT and BF, which were responsible for significantly extending electricity access and reducing poverty, energy poverty was not eradicated (Mazzone *et al.*, 2019). The merge of BF with *Auxílio-gás* caused a condition where people could opt to expend their cash benefits with modern fuels as LPG or other needs. From an energy poverty perspective, the program could not guarantee access to modern fuels, as some families returned to the use of biomass to spend their money with food or other goods (Gioda, 2019b; Mazzone, 2019a). Also, as observed before, the access to electricity by itself does not guarantee that all energy services are being consumed, and there are still some families that cannot enjoy all the benefits that electricity access has to offer (Grottera *et al.*, 2018).

Social programs must be frequently adjusted to understand possible risks associated with economic crises or any other future threat. The pandemic situation of COVID exposed the fragilities of the policies to eradicate poverty and energy poverty (Santos *et al.*, 2020). The number of people returning to the use of biomass has increased (GRUPO DE TRABALHO DA SOCIEDADE CIVIL PARA A AGENDA 2030, 2021), and late payment of utility bills are higher than before (Rosa, 2021). Also, climate change needs to be addressed in the discussion of energy poverty vulnerabilities (Schaeffer and Szklo, 2020).

Climate change may have a significant impact on the affordability of energy, since the electricity supply in Brazil is mostly based on hydroelectric power, as demonstrated by the current scarcity of rains in the country (Resende, 2021). The Brazilian situation, however, cannot be reduced to a single perspective. In a vast and heterogeneous country like Brazil, a regional comparative analysis is helpful to design policies targeting local differences, considering cultural, geographical and socio heterogeneity in their overall context.

Additionally, energy poverty needs to be observed integrating temporal dynamics and social resilience with the understandings of the need for energy service. Defining ‘energy vulnerability in the country should associate future risk factors that might contribute to the precariousness of access to energy services (Bouzarovski, Petrova and Tirado-Herrero, 2014).

Brazil's literature on energy poverty is still limited in addressing multidimensionality aspects and introducing temperature, and climate change, as a relevant variable. Energy poverty in Brazil has been mostly associated with the lack of access to modern fuels. Giannini Pereira, Vasconcelos Freitas and da Silva (2011) understood electricity access as a first step to eradicate energy poverty and energy inequalities in the country. The authors showed that with electrical access, many families could achieve a decent level of energy consumption and leave energy poverty. But the concept of minimum requirements adopted by the authors only considers lighting and cooking services and did not discuss how these basic forms of energy are just a primary condition to leave energy poverty situation, observing it from a broader perspective.

The use of the minimum requirement approach was also observed in Pereira, Freitas and da Silva (2010). The household's energy demand from those who acquired electricity access due to the LpT program was compared to those who previously had electricity. The authors defined an energy consumption basket following literature standards to outline energy-poor households. This approach does not represent regional needs and fails to discuss energy use in its different forms and functionalities. There was an improvement in the energy poverty condition due to the access to electricity. Still, the authors did not specify the energy services provided after the LpT program or discuss multidimensional aspects of energy use in places with new electrical connections.

Mazzone, Cruz and Bezerra, (2021) go further in discussing accessibility to modern energy fuels to define if a family is energy poor. A case study about energy use in an Amazon village was made. Most households in the case study live under the energy poverty line threshold defined by IEA and have limited electrical and LPG access. The authors argued that the concept of energy access goes beyond the classical duality between connected and not connected, and people who have electricity and access to LPG are far from not being energy poor. The affordability and electrical connection quality are essential for defining energy poverty status and should be considered a relevant metric. Moreover, there is a necessary discussion regarding fixed standards of eradication of energy poverty, and cultural and local aspects should be respected in the energy transitions efforts.

Affordability is crucial in identifying energy-poor households. Piai, Gomes and Jannuzzi (2020) focus on this economic dimension for defining energy poverty. The importance of the system cost is shown as a relevant element of understanding energy poverty and eradicating it. The concept of energy poverty and energy affordability is also discussed through the lens of low-income groups' vulnerability by Mazzone *et al.* (2019). The study examines the importance of social programs focused on low-income groups' purchase conditions to guarantee the population's energy needs.

It is possible to observe that Brazil still lacks efficient governmental programs to eradicate energy poverty. There is an inability to pay for energy that is widespread in the country and could not be solved in recent years (Mazzone; Cruz; Bezerra; et al. (2021) and Pereira et al. (2021)). Although there is important literature about energy poverty in Brazil, previous studies did not discuss all dimensions of deprivation in energy use that affordability issues can cause. Furthermore, thermal comfort was not well marked in Brazil in this context.

To address the issue of energy/fuel poverty and thermal comfort in Brazil, Mazzone (2020b) developed a case study in the Amazon region. The author understands and brings to discussion the multidimensionality of energy poverty in the rural Amazon and the climate-related challenges and solutions observed in the area. Affordability seems to be a critical concern for those who live in that area. The traditional thermal comfort solutions of households are threatened by a change in cultural and social status in that region.

Moreover, the thermal comfort needs have to be assessed from a climate change perspective. Mastrucci *et al.* (2019b) calculated the energy gap in different countries, including Brazil. This gap is defined by the exposed population that cannot adapt to the increasing temperatures of different climate change scenarios. The study goes beyond the definition of energy access and underpins the lack of essential space cooling appliances to guarantee thermal comfort. Developing countries are most vulnerable to those energy gaps, including Brazil. Also, demand for energy to fill the cooling needs could increase significantly depending on the climate scenario. Considering the location of those living under extreme weather situations, it is probably that many families could not afford these increasing energy needs (Mastrucci *et al.*, 2019b), reflected in terms of energy expenditure.

Clarke *et al.* (2018) analyzed the effects of climate change on buildings' energy expenses. The increase in energy demand and associated expenditures are observed globally and detailed for 12 regions. Low-latitude countries, including Brazil, are expected to have the highest growth in energy expenses. The increase in energy expenses is also a reflection of new adoption for AC (Randazzo, De Cian and Mistry, 2020).

A relation between AC ownership and climate change is observed in Pavanello *et al.* (2021). With a focus on Brazil and other emerging countries, the study shows that an increase in the use and adoption of AC appliances to adapt to climate scenarios is expected. But those dynamics are local-specific and depend on different factors, including income level. The ability to adapt and guarantee thermal comfort is socio-economic-related. The same is observed in Depaula and Mendelsohn (2010), where the temperature elasticity of electricity consumption is almost zero for low-income families, increasing in middle and high-income families. The results demonstrate the temperature vulnerability that can occur in certain social groups. The same is observed in other studies exploring the ownership of AC according to income level (Rao and Ummel, 2017; Grottera *et al.*, 2018).

Given the aforementioned, this study fills some gaps in the literature by associating climate change risks with poverty and energy poverty in Brazilian households. This work aims to assess the context of energy poverty in the country and how climate change may impact it, using historical analysis and identifying future risks for energy consumption in households. To do that, three different studies are presented, observing regional heterogeneities significant to understand Brazil.

The first study analyzes the benefits of electricity access in rural areas in terms of the multidimensional poverty index, HDI. Specifically, the study "The power of light: socio-economic and environmental implications of a rural electrification program in Brazil" evaluates the results of the program *Luz para Todos* in improving the socio-economic development in some Brazilian rural locations.

The second study, entitled "Understanding the multidimensionality of energy poverty in Brazil", seeks to understand energy poverty in its multidimensional forms and apply new indexes to Brazil. Through a historical analysis, it is possible to understand which dimensions of energy poverty were predominant in Brazil and which are remain nowadays.

The third study – "Impacts of a warmer world on space cooling demand in Brazilian households" – estimates Brazil's potential increase in energy consumption due to different climate changes scenarios. The impacts of climate change on household space cooling demand are assessed under three specific warming levels (SWLs) scenarios (1.5 °C, 2 °C, and 4 °C) and a baseline.

This thesis is divided into 5 chapters, being this introduction the first. Chapters 2 through 4 present each of the aforementioned studies. It is important to underline that these chapters can be read separately since they are individual, albeit connected, papers published or submitted to scientific journals. Chapter 5 gives the main findings of the studies and highlights how they can be used to a better design policies to eradicate energy poverty in Brazil. Also, chapter 5 suggests some potential future studies for a broader view of the problem

2 THE POWER OF LIGHT: SOCIO-ECONOMIC AND ENVIRONMENTAL IMPLICATIONS OF A RURAL ELECTRIFICATION PROGRAM IN BRAZIL

Paula Borges da Silveira Bezerra, Camila Ludovique Callegari, Aline Ribas, André F P Lucena, Joana Portugal-Pereira, Alexandre Koberle, Alexandre Szklo and Roberto Schaeffer

This paper was published on the volume 12 of Environmental Research Letters in 2017[1]. Since its publication there had been some updates on *Luz para Todos* program that should be mentioned here.

In 2018 the program was once again postponed by the law nº 9,357, and is now expected to end in 2022 (Eletrobras, 2021a). The new phase of *Luz para Todos* program intends to reach 420 thousand families living in rural that still lack electricity (Junior and Seabra, 2021). Until June 2021, the program executed 3.5 million new connections, reaching more that 16 million people (Eletrobras, 2021a).

Also, after 2017 another governmental program aiming to universalize electricity in Brazil was launched. Complementary to *Luz para Todos*, the program *Mais Luz para a Amazônia* (More light to Amazon, in english) focuses in bringing electricity to isolated communities living at Legal Amazon[2] region using only renewables energy systems. *Mais Luz para Amazônia* was created in 2020, instituted by Brazilian federal government through Decree No. 10.221 (Eletrobras, 2021b). The Program is expected to run until December 31, 2022 and should reach 70 thousand families (Ministério de Minas e Energia, 2020; Eletrobras, 2021b). Also, there is a possibility of extension until the completion of universal access to electricity in remote regions of the nine states that make up the Legal Amazon and will reach on that region (Ministério de Minas e Energia, 2020).

[1] DA SILVEIRA BEZERRA, P. B.; CALLEGARI, C. L.; RIBAS, A.; et al. The power of light: socio-economic and environmental implications of a rural electrification program in Brazil. Environmental Research Letters, v. 12, n. 9, p. 095004, 2017. Available at: <https://iopscience.iop.org/article/10.1088/1748-9326/aa7bdd>.

[2] Legal Amazon (*Amazônia Legal* in portuguese) corresponds to a delimited area of the Amazon region, in accordance with Article 2 of Complementary Law n. 124, of 03.01.2007. The region is made up of 772 municipalities in nine states: Rondônia, Acre, Amazonas, Roraima, Pará, Amapá, Tocantins, Mato Grosso and Maranhão. It has an approximate surface area of 5,015,067.75 km², corresponding to about 58.9% of the Brazilian territory (IBGE, 2020a).

Abstract

Universal access to electricity is deemed critical for improving living standards and indispensable for eradicating poverty and achieving sustainable development. In 2003,
2.1 the "Luz para Todos" (LpT – Light for All) program was launched aiming to universalize access to electricity in Brazil. The program focused on rural and isolated areas, also targeting to bring development to those regions along with electrification. This paper evaluates the results of the LpT program in improving socio-economic development in the poorest regions of Brazil. After an initial qualitative analysis, an empirical quantitative assessment of the influence of increased electrification rates on the components of the Human Development Index (HDI) is performed. The empirical results of this study showed that electrification had a positive influence on all dimensions HDI, with the education component having the strongest effect. Although complementary policies were needed to achieve this, results show that electricity access is a major requirement to improve quality of life.

Keywords: Electricity access, poverty alleviation, human development, Luz para Todos, Brazil

2.2 Introduction

Some 13 million people did not have access to electricity in Brazil in 2000. This represented 7% of all households in the country, around 3 million. The situation became even more alarming when considering the distribution of such households according to their income and location. From the aforementioned 3 million households, approximately 2 million were located in rural areas. This represented 29% of rural homes in Brazil at that time. Depending on the region, these numbers also varied significantly: around 1% of Southeast's households did not have access to electricity, while in the North almost 18% were in that situation (IBGE, 2000).

Electrification provides a solid basis for development of local communities. Once a community has access to electricity, it can also have access to safe potable water, better health conditions, food security, as well as lighting and information. In addition, it reduces the need for collecting and using other traditional sources of energy, such as firewood, animal dung, and crop residues for cooking and heating (Goldemberg, 2001), which cause harmful indoor air pollution (WHO, 2014). In poorly ventilated dwellings, indoor smoke can be one hundred times higher than acceptable levels, causing significant health damages (WHO, 2016). Access to electricity not only releases people from hard work, but also increases productive working hours and provides opportunities for self-employment, in particular for women in rural areas (Dinkelman, 2011).

Universal access to electricity is not only critical for improving living standards but deemed indispensable for eradicating poverty and achieving sustainable development (GNESD, 2007). Because this is widely accepted today, ensuring universal access to affordable electricity by 2030 was incorporated directly in the Sustainable Development Goals (SDG) (United Nations, 2015). Increasing income by itself cannot guarantee some basic services and needs and cannot improve living conditions if it is not combined with infrastructure (UNDP, 2002; Cook, 2011).

A National Program of Universalization of Access and Use of Electricity (Light for All), the “Luz para Todos” (LpT) program, was launched by the Brazilian government in 2003 with the goal of extending access to electricity to all rural communities in the country.

Some studies evaluated the extent to which the LpT program increased income and promoted the social inclusion of benefitted communities (Pereira, Freitas and da Silva, 2010; Gómez and Silveira, 2012; Coelho and Goldemberg, 2013; Slough, Urpelainen and Yang, 2015). However, there is a lack of formal empirical assessments that attempted to quantitatively measure the socio-economic improvements associated with the LpT program.

This paper evaluates the results of the LpT program in improving socio-economic development in the poorest regions of Brazil. To do so, an initial qualitative analysis is made based on existing data, literature and assessments of the program. On a second stage, an empirical quantitative assessment of the program’s results is performed, which contributes to the existing body of analysis on the impacts of rural electrification in the country.

This paper is organized in five sections. Following the introduction, a background section overviews the socio-economic context of the LpT program and its policy framework. From this point, in Section 3, implications for economic, social and environmental development are unveiled qualitatively. Section 4 details results of the empirical assessment conducted to quantitatively measure the socio-economic improvements associated with the program. This is followed by final remarks.

2.3 Background

Inequality in access to electricity was a reality since the introduction of this basic service in Brazil. It is hard to say precisely when the Federal Government started to put efforts on the electrification process. In fact, electricity came as a natural consequence of the urbanization process that occurred during the 1940s and 1950s. With low population density and large distances between properties, rates of electrification in rural areas have always been lower than in urban regions (Bittencourt, 2010).

The first efforts to promote rural electrification in Brazil started with the creation of rural cooperatives, after the 1940s. Rural cooperatives were an initiative created by local communities to be able to finance the installation of transmission lines and guarantee access to electricity. During the decades that followed, other initiatives took place, for instance: the Rural Electrification Fund (FUER – Fundo de Eletrificação Rural, in Portuguese), created in the mid-1950s; the Executive Group for Rural Electrification (GEER – Grupo Executivo de Eletrificação Rural, in Portuguese), created in 1970; the First and Second National Rural Electrification Plan (PNER – Plano Nacional de Eletrificação Rural, in Portuguese), implemented during the 1970s; the Program for Energy Development of States and Municipalities (PRODEEM – Programa de Desenvolvimento Energético de Estados e Municípios, in Portuguese), launched in 1994; and later the Light in the Countryside (Luz no Campo, in Portuguese), created in 1999.

Figure 1 shows the rate of electricity access in Brazil between 1950 and 2000. Despite the evolution observed after the 1970s, there were still significant differences between the level of electrification in urban and rural areas. In 1991, 97% of the population of urban areas already had access to electricity, while, in the countryside, this number did not reach 50% (ANEEL, 2005)

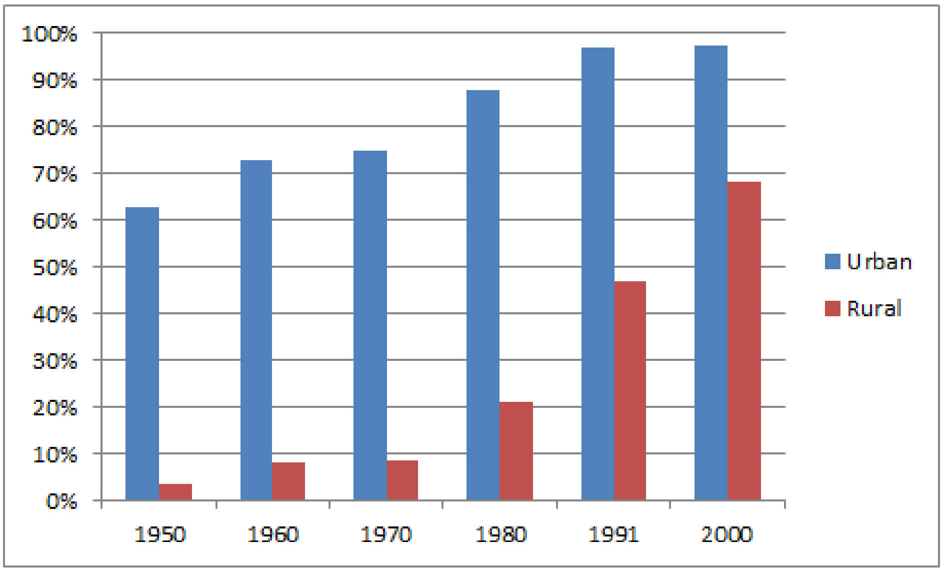

Figure 1: Evolution of residential electrification in Brazil (ANEEL, 2005)

2.3.1 The National Program of Universalization of Access and Use of Electricity – LpT (Light for All)

In November 2003, the LpT Program was established by decree No 4,873. The program was coordinated by the Ministry of Mines and Energy (MME) and came as a consequence of Law 10,438 of 2002 that had set parameters to guarantee universalization of electricity. The program aimed to increase the electrification rate in the country, providing power to 10 million people until 2008, especially those living in rural areas (BRASIL, 2003). This was the first social oriented electricity access policy in Brazil, in which beneficiaries did not have to contribute financially (Goldemberg, Rovere and Coelho, 2004). To meet this initial goal, US$ 2.3 billion were invested. The program was extended first until 2014 and more recently until 2018 (MME, 2017). Until May 2016, it had reached 15.6 million people, with an overall investment of US$ 7 billion.

Rural electrification was seen by the government as a key element to achieve social development in rural areas. Thus, projects with higher social development outcomes were highly ranked and prioritized, when compared to those with limited social benefits. New electricity demand was identified through the so-called Luz para Todos' agents (LpT agents). These agents worked close to local communities, informing about the program execution and its benefits. During the work execution, LpT agents were also responsible for identifying, together with communities, possible productive uses for electricity and complementary actions of social inclusion. Besides, these agents acted as a communication channel between local citizens and program executors. Rural populations were able to request new electrical connections through the LpT agents. In this way, communities were partially involved in the program's decision-making process, helping to recognize population needs for demand and productive applications of electricity in the region. Also, utility companies conducted educational and awareness campaigns about appropriate, efficient and secure use of electricity (Gómez and Silveira, 2010).

Technically, the program focused on low-cost transmission and distribution grid extensions. Alternatively, where connection to the grid would not be feasible, electricity could come from decentralized generation grids in isolated systems. To be approved, the construction plan had to detail the technical, material and equipment criteria to be used.

Decentralized generation projects must be cost competitive with grid extension to be endorsed (MME, 2004). Also, for decentralized and isolated system generation, the projects must consider environmental aspects, end-user capacity building, and overall sustainability. The technological options for off-grid generation foreseen by the program are hydro, wind, diesel fuel and biomass, with special focus given to solar in recent operational manuals. The program, therefore, did not clearly promote the deployment of renewables until recently. This is, actually, one of the critical aspects of Brazil's universal energy access strategy.

After the initial period of the program (2004-2008), LpT was extended four times. During the initial execution, between 2004 and 2008, the program could not reach its initial target of providing access to 10 million people. In addition, agents also identified a higher number of families with no access to electricity than the number accounted for in the year 2000 Census. This new demand was related to population growth, not considered before, and to the return of some families to rural areas. These facts led to the implementation of new phases of the program, continuing it and setting new targets (MME, 2008). Table 1 summarizes the initial targets and achievements of each phase of the LpT program.

Table 1: Summary of the different stages of the LpT program

Phase	Period	Goals and achievements
Phase I	2004 – 2008	Provide universal power access to rural communities not connected to the grid
Phase II	2008 – 2010	Provide power access to 1 million families that had not been connected in the first stage, reaching almost 3 million households
Phase II-extension	2010-2011	Provide electricity access to isolated communities, areas with no connection to distribution lines, low population density, difficult access and poor infrastructure, reaching further 1.7 million new electrical connections.
Phase III	2011-2014	As the majority of the population already had access to electricity, the focus of this extension was to reach communities living in areas with significant logistic and infrastructure difficulties, particularly in the North and Northeast regions. The target for the period was the connection of 795 thousand new households (MME, 2011b).
Phase IV	2014-2018	Expected to provide power access in isolated areas and the Amazon region.

Source: (Bezerra *et al.*, 2016)

2.3.2 Challenges and overall evaluation

Despite the impressive numbers of the LpT program, the target of giving electricity access to all of the Brazilian population has not been achieved yet. The extension of the grid could readily benefit a significant number of people, but as the grid extension approaches its physical and economic limits, reaching some areas becomes difficult or even unfeasible. Therefore, universalization goals become increasingly difficult to achieve (Gómez and Silveira, 2015).

The Brazilian national grid structure has a centralized structure, concentrated on the coast, which is very effective to meet industrial consumers and urban area needs, but fails to promote electrification of isolated communities, especially in the Amazon region. This structure makes connecting island regions to the grid a hard task and a challenge to reaching households far from urban centres in a vast country of continental dimensions. In terms of institutional structure and operations, LpT prioritized the extension of the grid (Slough, Urpelainen and Yang, 2015).

As the program proceeded, the need for off-grid solutions increased. The program reached its limits in connecting areas closer to the grid and the average cost per connection increased, creating a challenge to take electricity to isolated areas far from the existing grid. In this context, less expensive technological alternatives should be considered, since utilities would pressure for high tariffs to compensate this adverse situation (Di Lascio and Barreto, 2009). Capital costs to electrify most isolated communities can be twice as high than new grid connections (Sánchez, Torres and Kalid, 2015).

Observing the connections made by year, it can be noted that fewer new connections were made as time passed (Figure 2). After 2010, Brazil achieved 98.6% electrification rate, but the remaining 1.4% became harder to reach. The third phase of the program, after 2011, faced this challenge, and the connections in 2013 and 2014 were lower than 100 thousand/year.

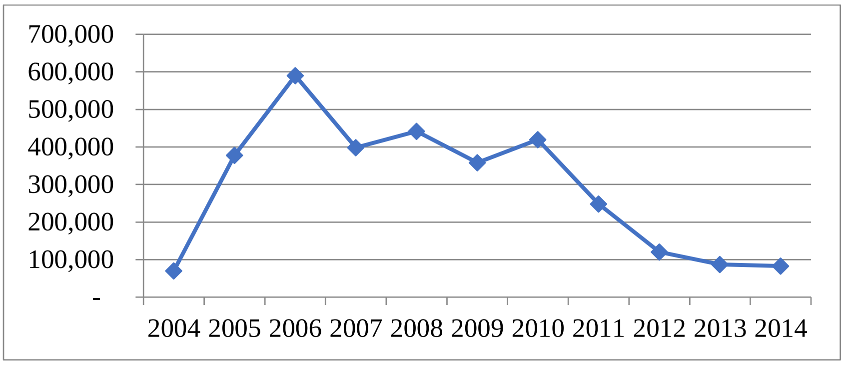

Figure 2: New electrical connections made by year (EPE, 2015; Agência do Senado, 2016)

According to Pereira et al. (2010), in order to reach isolated communities it is necessary that decision makers work together with regulatory agencies, universities and research centres. The efforts must include the development of cleaner technologies and improvement of management models, respecting the cultural, economic and environmental aspects of using renewable technologies in a decentralized or self-generation manner.

In the case of the Amazon region, challenges are even harder. The region has an extensive area with a complicated topography, surrounded by rivers and highly dense rainforest. In addition, it has a very small and low-density population with low-income levels, and mostly concentrated in rural areas (Gómez, 2014). These particular characteristics pose specific challenges to providing electrification in that area. The people that already have access to electricity are concentrated in regions with previously existing physical grid infrastructure. Cities and communities are mostly located in regions of high deforestation, with highways and agriculture, which facilitated the connection with the national electric grid. However, this is not the case for many parts of the region (Di Lascio and Barreto, 2009).

Currently, there are mainly three obstacles to foster universal access to electricity in remote areas. The first one is the need to adapt the existing institutional structures. The second is the choice of technology or supply solutions that comply with the local environment and infrastructure. The third one is a more effective use of government funds within the context of the current subsidy scheme. A new rural electrification model in which local, resource-based technologies are supported by an adapted institutional framework and existing funding structures is needed to reach this last mile (Gómez and Silveira, 2015). Finally, a major challenge is related to guaranteeing the continuity of electricity affordability for low-income households benefitted by LpT after the end of the Program. Actually, electricity affordability is being sustained by cross-subsidies provided by the Brazilian interconnected electricity system, in order to compensate the higher costs incurred by local power utilities to serve remote areas. After 2018, it is not yet clear whether and how these subsidies will be maintained (Agência do Senado, 2016).

2.4 Implications for economic development, social welfare and environmental sustainability

The LpT program exceeded the initial target of providing electricity access to 10 million citizens. During its 10 years of execution, the program reached over 3.3 million households, equivalent to more than 15 million people (MME, 2016). More than enabling access to electricity, an important benefit of the program was recognizing electricity supply as a way to promote social and economic development in less developed regions of the country. The program was a key component of the national strategy for poverty reduction, sustainable development and reduction of social inequality (Gómez and Silveira, 2010).

Therefore, the results of electrification projects should not be measured just by the number of new households connected, but also by the social and economic benefits promoted by electricity access. Identifying social, environmental and infrastructure evolution caused by the implementation of the LpT policy is critical to understanding the welfare improvement and evaluating the return of the capital invested in the program

(Gómez and Silveira, 2010). Table 2 identifies potential improvements to welfare associated with electricity service in rural areas (Motta and Reiche, 2001).

Table 2: Electricity service related to improvements in types of uses

Household Social and Community Uses	Productive Uses	Education Uses	Health Uses	Public Administration Uses
Improved quality of life (light, TV, radio). Light: children and women gain additional time at night (reading, homework) Improved light quality (200 times brighter) and cost per lumen. Reduced cooking times and easier cleaning due to illuminated room. Increases productivity for self-consumption. Safety: Street lighting allows children and women to socialize at night. Facilitates community activities (light, TV, radio, discotheques). Potential effect on birth-rates.	Raises productivity: increased profit and employment. E.g. light extends work time; electricity allows applications such as water pumping (irrigation), soldering, motive applications (drilling, sawing, mills), cold chain (e.g. for small shops and restaurants, milk processing, beef storage), fish ponds, electric fences, video, cinemas, etc. Permits use of ICT.	Studying at night; adult education; allows retention of qualification teacher. Schools can serve as anchor clients for service providers. Subsidizing public services is an efficient way of targeting subsidies with reduced free rider effects.	Light for emergencies, childbirths; vaccine fridges; HIV. Domestic light seems to be correlated with more whitewashed walls and less bugs	Allows for more efficient public administration. Increase working time and improves quality of service.

Source: Motta & Reiche (2001)

Table 2 shows that electricity uses are associated with many dimensions of development. Not only can the population have the choice of consuming electrical appliances, but also education and health improvement can be achieved. Moreover, electrification can change the local reality in terms of social, economic and environmental aspects.

2.4.1 Environmental aspects

Access to electricity can change in many forms the way of living in a community. In addition to social and economic impacts related to electrification, there are also some environmental impacts. One of the main choices in the electrification process is which energy sources to use in isolated areas, where grid connection is not possible.

Electricity generation in Brazil is highly based on renewable energy sources. In 2014, 77.2% of total electricity supply was provided by renewables sources. This contrasts with only 28.2% in isolated areas, where fossil fuels are responsible for 71.8% of electricity generation. To supply the county's electric system in 2014, 78.30 MtCO2 were emitted, from which almost 10% came from isolated systems where electricity consumption is only 0.8% of total demand in Brazil. In that sense, the choice of supply source for isolated systems is critical for improving energy access without increasing total greenhouse gas (GHG) emissions (EPE, 2015).

Historically, thermal-power plants fueled by diesel were the main supply choice for isolated systems, but renewable energy systems are being increasingly regarded as a favorable option for providing power to isolated communities. Despite the higher capital cost, generation from renewable sources can have lower operational costs. When considering local realities of isolated communities, the use of renewable energy options can be a preferable solution to providing electricity access (Di Lascio and Barreto, 2009; Gómez and Silveira, 2015; Sánchez, Torres and Kalid, 2015).

The use of government incentives in the form of laws, technological research and institutional frameworks is important to change the current fossil-fuel-based generation in isolated communities (Pereira, Freitas and da Silva, 2010). The LpT program can be considered as a mean to foster the use of renewable energy sources. In November 2008, the MME promoted activities to assist local utilities in developing and implementing small projects for electricity supply using renewable energy sources. These activities were executed with the support of Inter-American Development Bank (IDB) and focused on training professionals and utilities to find solutions based on local capacities for using alternative energy sources (Barreto *et al.*, 2008).

Also, after 2009, the LpT program launched special project guidelines with the main objective of developing the use of renewable energies in areas with difficult access, by preferably funding projects in isolated regions with the use of renewable energy sources considering the region's potentials. There is a significant potential for increasing electricity access in isolated systems through the use of PV, biomass, and small hydro. In addition to being appropriate to local reality, these projects also guarantee electricity supply with lower environmental impacts, and energy independence for the communities (Di Lascio and Barreto, 2009). Sánchez et al. (2015) evaluated the most significant rural electrification projects using renewable sources in isolated areas of the Brazilian Amazon region during the first stages of the LpT program (2003 to 2011). These projects showed the convenience of substituting, totally or partially, the use of diesel, which had to be shipped in. More importantly, they showed that electricity generation from local renewable sources is a way of empowering disadvantaged communities, giving them energy independence along with the benefits of electricity access.

Pereira et al. (2010) compared the energy consumption mix of an average household before and after getting access to electricity (Figure 3). Before access to electricity, LPG, firewood and diesel combined represented 90% of total energy demand, the remaining 10% was due to the use of charcoal, gasoline, kerosene and others, from a total of 5.16 GJ/year/per capita. After getting access to electricity, the total consumption increased 28%, and the share of those energy sources dropped to 65%. Also, it is worth highlighting the fast penetration of electricity, reaching 34% of the average energy consumption basket. The control group confirmed that electricity access was responsible for this change in the composition of the average household's energy basket.

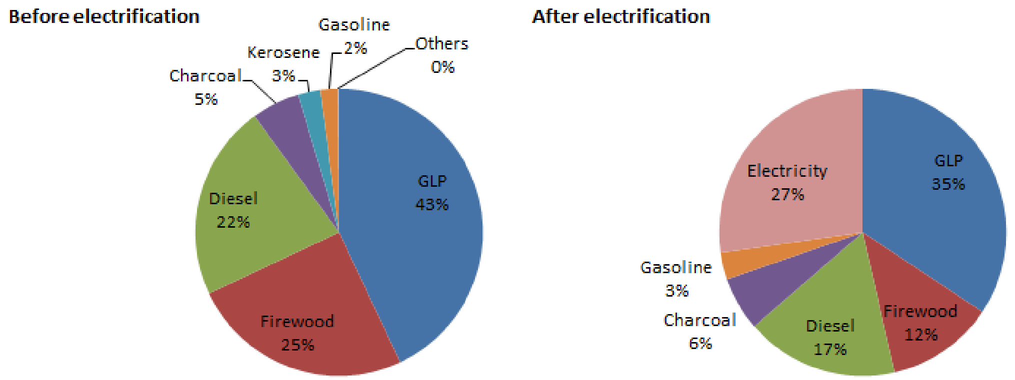

Figure 3: Energy consumption profile of a Brazilian household before and after the access to electricity – Pereira et al. (2010)

Changes in the energy basket used by households were also observed in a national survey made in 2013 with beneficiaries of the LpT program. This survey showed a transition in a family's energy basket from kerosene lamps and candles as the main sources of lighting. After accessing electricity, family expenses with kerosene, diesel, oil, gas and batteries dropped to half the initial values, indicating a substitution of fossil fuel sources by electricity (MDA Pesquisas, 2013b).

Concerning land use impacts, electrification can have two opposing effects as a result of changes in agricultural productivity. Electricity access can lead to an improvement in agricultural productivity, as it allows a more efficient irrigation with the use of water pumps, as shown in Assunção et al. (2015). The study suggests that a 10% increase in electrification could lead to a 0.66 percentage points increase on the proportion of farms with irrigation and a 9.8% increase in agricultural production per hectare.

However, the same study found that such improvements can lead to two opposing effects on the protection of forests and native vegetation: (i) an expansion of farm size and/or frontier land conversions, and (ii) a shift away from cattle ranching, which is more environmentally destructive, and into crop cultivation, allowing farmers to retain more native vegetation within rural settlements. Even though the authors estimated that electrification caused a small net decrease in deforestation in a specific region in Brazil, decreases in deforestation cannot be correlated to higher electricity access given that it depends on many other key variables, including the type of agricultural crops involved. Yet, electricity can add value to local traditional production of extracted products from native forests reinforcing subsistence agriculture, which can account for a high share of family income. Therefore, extensive agriculture is not used as a substitute for improving family income and local vegetation can be preserved (Di Lascio and Barreto, 2009).

2.4.2 Socio-economic development

To measure socio-economic impacts, a survey developed by (MDA Pesquisas, 2013a) evaluated the profile of beneficiaries and the impacts of the program in the communities. Results show that 89.8% of the beneficiary families had a total monthly income equal to or below two times the minimum wage and 18.8% only received half the minimum wage. Nearly half of the targeted families were rural workers. Among the families interviewed by the program's survey, 41.2% considered that the program brought income rise and 40.5% saw an increase in the amount of job opportunities. This adds to the evidence of the positive social and economic co-benefits of the program.

The income per capita in each state between 2000 and 2010 improved significantly. Regions, such as the Northeast and Midwest, showed a higher monthly income in 2010 than in 2000. The Southeast and South regions had the highest electrification rates and income per capita in 2000, while the lowest values were in the North and Northeast regions, for both cases. In 2010, an improvement could be observed in the latter regions in both dimensions.

Table 3 compares electrification rates and per capita income in each Brazilian State in 2000 and 2010. The greatest increases in electrification rates were in poorest and largely rural States (mostly in the North and Northeast regions). Generally speaking, the regions with the highest electrification rates also had a higher income increase in the same period.

Table 3: Brazilian situation in 2000 and 2010: electrification rate and income per capita by state

Brazilian States	Region	households with electricity			Per capita income		
		2000 (%)	2010 (%)	2000-2010 Growth rate (%)	2000 (US$)	2010 (US$)	2000-2010 Growth rate (%)
Brazil		93.5	98.6	5.5	182.91	245.10	34.0
Acre (AC)	North	75.8	91.1	20.2	111.34	161.21	44.8
Alagoas (AL)	Northeast	89.8	99.0	10.2	88.08	133.55	51.6
Amazonas (AM)	North	82.2	92.2	12.2	108.56	166.66	53.5
Amapá (AP)	North	95.1	98.3	3.3	131.08	184.93	41.1
Bahia (BA)	Northeast	80.9	96.5	19.2	99.43	153.36	54.2
Ceará (CE)	Northeast	88.2	99.1	12.3	95.77	142.21	48.5
Distrito Federal (DF)	Midwest	99.7	99.9	0.2	370.31	529.52	43.0
Espírito Santo (ES)	Southeast	98.7	99.8	1.2	177.27	251.75	42.0
Goiás (GO)	Midwest	97.3	99.4	2.2	176.44	250.38	41.9
Maranhão (MA)	Northeast	78.7	96.1	22.2	67.39	111.25	65.1
Minas Gerais (MG)	Southeast	95.7	99.4	3.9	169.46	231.46	36.6
Mato Grosso do Sul (MS)	MidWest	95.6	98.6	3.2	177.93	246.79	38.7
Mato Grosso (MT)	MidWest	89.5	98.0	9.5	179.88	235.42	30.9
Pará (PA)	North	76.7	91.9	19.8	103.66	137.93	33.1
Paraíba (PB)	Northeast	94.5	99.4	5.3	92.34	146.63	58.8
Pernambuco (PE)	Northeast	95.5	99.5	4.2	113.40	162.28	43.1
Piauí (PI)	Northeast	74.5	93.0	24.9	78.66	128.72	63.6
Paraná (PR)	South	97.7	99.6	2.0	197.06	275.05	39.6
Rio de Janeiro (RJ)	Southeast	99.5	99.9	0.4	255.03	320.87	25.8
Rio Grande do Norte (RN)	Northeast	94.1	99.4	5.6	108.37	168.39	55.4
Rondônia (RO)	North	83.9	97.3	15.9	144.23	207.11	43.6
Roraima (RR)	North	86.0	90.7	5.5	142.69	186.97	31.0
Rio Grande do Sul (RS)	South	97.8	99.7	1.9	218.62	296.15	35.5
Santa Catarina (SC)	South	98.6	99.8	1.2	214.21	303.77	41.8
Sergipe (SE)	Northeast	91.8	99.2	8.1	100.86	161.63	60.3
São Paulo (SP)	Southeast	99.6	99.9	0.3	272.43	334.81	22.9
Tocantins (TO)	North	77.2	94.7	22.7	106.33	181.11	70.3

Source: IPEA & WWP (2014)

Although a causal relationship between the electrification process and income cannot be inferred, a correlation between them can be noticed (IPEA and WWP, 2014). It is important to mention that after 2003 other governmental social programs were established with the objective of reducing poverty in all dimensions. The main program was Bolsa Família, a cash transfer social program. By August 2016, the program had benefited 13.8 million families, with an average cash transfer of US$ 56.00 per month per family (MDS, 2016). This will be further explored in Section 4.

Bolsa Familia was integrated with many other programs, such as LpT. The government understood that a monthly stipend was by itself not enough to lift most of these individuals and their families out of extreme poverty. In conjunction with LpT, however, Bolsa Família's benefits made it possible for families to make use of electricity benefits, investing in appliances, for studying, or for small family businesses (Freitas and Silveira, 2015).

In the regions included in the LpT program (most of them rural areas), the rise in income levels can be associated with more productive rural activity, as well as the diversification of economic activities. Electrification allows the creation of small businesses, such as bakeries, local markets and drugstores. After LpT, for instance, the presence of local markets, bars and bakeries increased 24%, 22% and 7%, respectively (MDA Pesquisas, 2013a).

Also, according to MDA Pesquisas, (2013a), 462,000 new direct and indirect jobs have been created as a result of the program implementation, and around 244,000 women started in a productive activity (MDA Pesquisas, 2013a). In addition, in another survey made in the State of Tocantins, in the North region, Guimaraes (2011) reports the economic improvements triggered by the LpT program. The author presented two case studies on how electrification increased both productivity and family income in rural areas. Guimaraes (2011) also reveals that after electrification, communities were able to increase their income and expand their economic activities. For instance, farmers were able to use electrical machinery in farming and processing activities, which increased their productivity considerably. In some cases, households increased their income by 250%.

According to MDA Pesquisas, (2013a), almost all beneficiaries reached by the program have reported improvements in their quality of life, mainly due to comfort and home needs. According to Pereira et al. (2010), what distinguishes a poor household from a better-off one is also the wide range of choices in terms of which fuels to use (more efficient, more convenient, less polluting, etc.) and which equipment and appliances to buy. The government appraises that US$ 2.0 billion were injected in the household appliances market due to the LpT program, through electrical appliances bought by beneficiaries of the program. It is estimated that 81% of families purchased new TV sets, 71% refrigerators and 62% cell phones. Considering all the appliances, a total of 14 million new pieces of equipment were bought.

MDA Pesquisas (2013a) also measured social impacts associated with the electrification process. A survey with program beneficiaries showed an improvement in public services (e.g. education) and welfare. Most of LpT program beneficiaries believe that morning and night shift educational activities were improved. In addition, according to the survey, 309,000 women were enrolled in primary and secondary schools. The survey also evaluated the population opinion about health services. Nearly half of the beneficiaries believed that health care improved given the better access and quality of health centres.

Despite the results, poverty is a complex and multidimensional phenomenon; as so, it cannot be reduced to a single component, as electricity. It is also important to understand the role of other government programs in Brazil. Bolsa Família was the main program at that time, with the goals of reducing poverty, promoting food security, and increasing access to public services, especially health, education, and social assistance. Since it was launched, 5 million people left extreme poverty living conditions, reducing inequalities in Brazil (Fultz and Francis, 2015).

As mentioned by Soares (2012), the strategy of the Brazilian government has been based on the complementarity of programs. These include adult education, opportunities for youth, job training, labour intermediation, subsidized electricity, rural electricity grid expansion (LpT), rural extension of microcredit to those who either are or may soon be Bolsa Família beneficiaries. The integration of complementary programs and actions contributes to families' socio-economic inclusion and their emancipation from the program in a long term perspective (Quinhões and Fava, 2014). Bolsa Família can be considered a driver of the social achievements observed, and electrification process is one of the important keys used to give possibilities to many families to alleviate poverty. Therefore, electricity has a role to make the development possible, not by itself, but integrated to other social efforts.

Despite the several evaluations of the results of the LpT program, there is a lack of formal empirical assessments that attempted to quantitatively measure the socio-economic improvements associated with the LpT program. The empirical assessment performed in this paper is an attempt to complement some knowledge gaps on the effects of the LpT program by performing a statistical analysis at the municipality level in Brazil.

Empirical Assessment of the results of the LpT program

When the program was launched, nearly 90% of the target families that did not have access to electricity had low income – up to 3 times the minimum wage – and lived in
2.5 areas with low HDI (Eletrobras, 2016). It is expected that electricity supply has a large impact on well-being in regions with low HDI by improving health, education and communication services (Gómez and Silveira, 2010). Actually, the role of advances in energy services in improving the HDI of a country at early stages of development is demonstrated by some studies (Pasternak, 2000; Martínez and Ebenhack, 2008; Jackson, 2009; Steinberger and Roberts, 2009, 2010). In this context, the HDI can be one way to analyse the success of a policy.

The Brazilian government uses the HDI as a tool for planning and monitoring development policies, including the LpT program (Gómez and Silveira, 2010). Comparing 2000 data on development with observed electrification growth shows that low HDI levels were a reality in areas with the lowest electricity attendance.

According to PNUD et al. (2016), in 2000, North and Northeast regions presented the lowest HDI in Brazil and also the lowest electrification rate at the time, just 87.7% in the Northeast and 81.6% in the North. On the other hand, more developed States, like the Federal District and São Paulo, had high HDI and presented high electrification rates (respectively, 99.7% and 99.6%). Regarding the evolution of the HDI between 2000 and 2010 in each Brazilian state, four states had improvements in electrical coverage higher than 20%: Acre, Maranhão, Piauí and Tocantins. All of them had progress in the HDI levels of around 30%, Maranhão being the state with the highest improvement, 34.2%, with an increase in the HDI from 0.476 to 0.639. According to 2010 data, all Brazilian states left the group of lowest human development regions, and were considered to be medium development regions, with HDI levels higher than 0.600. At the time, the lowest HDI was in the state of Alagoas (0.631). It is worth mentioning, however, that HDI in Alagoas in 2000 was 0.471.

(Borges Da Cunha, Walter and Rei, 2007) shows that correlation between HDI levels and total per capita electricity consumption for 177 countries and 27 Brazilian States are similar to most countries with medium development levels. Also, statistically, there is a significant correlation between residential electricity consumption and HDI, as found by

Pasternak, (2000), Kanagawa & Nakata (2008), Martínez & Ebenhack, (2008), Steinberger & Roberts (2009), Mazur (2011) and Oliveira (2013).

In the Amazon region, Gómez & Silveira (2010) finds evidence about the relationship between per capita residential electricity consumption and HDI. The author concludes that, if electricity access is provided to those with low HDI, a significant improvement in HDI can be achieved. Strong benefits can apparently be achieved in the Amazon region, as electricity helps break isolation and increases opportunity for the socio-economic inclusion of many communities.

Slough et al. (2015) examined the correlation between HDI in Brazilian municipalities in 2000 and the improvements in electrification rates between 2000 and 2010, during the LpT program. The study reveals that the improvement in electricity access goes along with an increased HDI and increased per capita income. In each case, the association was strong and suggested that rural electrification and socio-economic development are closely linked. The study also found that electrification efforts made by the LpT program seems to have achieved more success in municipalities that had a low electricity access rate but a relatively high HDI, implying that the drive to bring electricity to the countryside brought the most benefits to municipalities that were already doing relatively well in other development-relevant measures. In contrast, municipalities that previously had both low electrification rates and a low level of socio-economic development appear to have fallen further behind in relative, if not in absolute terms.

In that way, to Slough et al. (2015) the strong correlations found cannot tell us whether electrification drives development or development drives electrification. The study concluded that the LpT program targeting poor communities is important for reducing inequality of electricity access, but not sufficient to drive transformational development effects, since the latter depend on the government's ability to promote economic growth and social development. Complementary interventions are necessary to allow local communities to exploit rural electrification for productive uses, not limiting electricity access for the provision of basic household services. In fact, it is equally possible that LpT actually targeted the most advanced municipalities and did not contribute much to development itself. Despite the correlation observed in the studies, HDI evolution cannot be inferred as a result of the electrification process. However, the latter is unarguably a pre-condition for high HDI levels. The social benefits regarding electrification access can only be achieved if other actions are executed jointly with the electrification process.

An empirical quantitative assessment of the program's results based on a panel data regression model is proposed to assess the relationship between HDI and its components and electrification rate and, thereby, provide further insight into the socio-economic impacts of rural electrification in the country.

2.5.1 Database

The database used in this work was constructed from the concatenation of Brazilian population data from Brazilian Institute of Geography and Statistics (IBGE, 2020b) and the Atlas of Human Development in Brazil (PNUD, IPEA and FJP, 2016), which provides the Municipal Human Development Index (MHDI) and other 200 indicators for demography, education, income, labour, housing and vulnerability of Brazilian municipalities.

The database was constructed at the municipal level, including observations for the 5565 municipalities from all of the 27 Brazilian states for the years 2000 and 2010. The period was selected according to the availability of information.

Descriptive statistics of all variables, as well as the correlation matrix, were calculated. The results are found in the ANNEX 1. The correlation matrix seeks to contribute to the verification of correlation between the explanatory variables. Variables used in the estimations, as well as their theoretical and empirical references are described below (PNUD, IPEA and FJP, 2016).

The dependent variables used by this study are the human development index and its three basic dimensions – income, education and health – as described below.

a) Municipal Human Development Index (MHDI): Municipal Human Development Index. Geometric mean of the indices for the Income, Education and Longevity dimensions, described below.

b) Municipal Human Development Index - Education Dimension (MHDI_E): is obtained by the geometric mean of the frequency of children and young people at school, with weight of 2/3, and the education of the adult population, weighing 1/3.

c) Municipal Human Development Index - Longevity Dimension (MHDI_L): is obtained from the indicator of life expectancy at birth, using the formula:

$$\frac{(O - Min)}{(Max - Min)}$$

Equation 1

Where: O is the observed value of the indicator; Min is the minimum value; Max is the maximum value and the minimum and maximum values are 25 and 85 years, respectively.

d) Municipal Human Development Index - Income Dimension (MHDI_Y): is obtained from the per capita income indicator, using the formula:

$$\frac{(ln\ (O) - ln\ (Min))}{(ln\ (Max) - ln\ (Min))}$$

Equation 2

Where: O is the observed value of the indicator; Min is the minimum value; Max is the maximum value and the minimum and maximum values are R$ 8.00 and R$ 4,033.00 (at August 2010 prices).

The explanatory variables used in the study were as follows:

a) Share of the population living in households with electric power (I_LIGHT): the ratio of the population living in permanent private households with electricity access to the total population living in permanent private households, multiplied by 100.

b) Bolsa Família control variable (V_BF): financial amount passed on to municipalities for the management of the Bolsa Família family grant program (in Brazilian Reais).

2.5.2 Methodological approach

2.5.2.1 *Municipalities selection*

There are no official data about the actual municipalities that took part in the LpT program. Therefore, it was necessary to identify and filter the municipalities that were served by the program based on the variation of the rate of electrification: all municipalities that had an increase above 40% in the period were considered in the analysis. By applying this selection criteria, 805 municipalities were selected, comprising 12 million people in 2010, the approximate number of people served by the program according to MME (2017).

2.5.2.2 *Panel data regression model*

A panel data regression model was used to assess the relationship between the HDI and its components and electrification rate, in particular, the estimates assuming random and fixed effects will be presented, as well as the robustness tests to choose the best econometric model.

The regression models with panel data combine time series and cross-sectional observations. Therefore, there are more observations and additional degrees of freedom compared to the specific use of cross-sectional or time series analysis (Baltagi, 2001; C, 2003).

For modelling the unobserved effects there are two possibilities, both of which were tested: the fixed effects and the random effects. The fixed effects model considers that the specific intercept of each individual can be correlated with one or more regressors. As for the random effects model, it assumes that the (random) intercept of an individual unit is not correlated to the explanatory variables (Wooldridge, 2010). In this case, when considering that the variables are not correlated, the random effects method is more appropriate. On the other hand, if the unobserved effects are correlated to some explanatory variable, the estimation by fixed effects would be more appropriate. For the selecting the method – fixed or random effects – the Hausman test will be performed (Wooldridge, 2010).

The econometric model adopted is represented by the Equation 3:

$$Y(i,t) = \alpha + \beta 1 * I\_LIGHT(i,t) + \beta 2 * V\_BF(i,t) + \varepsilon(i,t$$

Equation 3

Where: Y(i,t) represents the dependent variable for municipality i in period t (MHDI, MHDI_E, MHDI_L, MHDI_Y); α is the intercept; β1 and β2 are the parameters to be estimated; I_LIGHT(i,t) and V_BF(i,t) are the explanatory variables; and ε(i,t)represents the error term.

2.5.3 Results

The results for the random effects and the fixed effects regression models were sequentially estimated using Equation 3. The Hausman test rejected the null hypothesis that the random effects are consistent, pointing out that the best selection is the fixed effects modelling. The estimation results and the test performed are shown in Table 4.

Table 4: Panel regression model results

	Coefficients[a]	
	Random Effect	Fixed Effects
Dependent Variable: MHDI		
T_LIGHT	0.2286	0.2054***
V_BF	0.0245	0.0258***
R^2	0.90	0.95***
Hausman test	0.008956	
Dependent Variable: MHDI_E		
T_LIGHT	0.2286	0.5210***
V_BF	0.0245	0.0543***
R^2	0.90	0.94***
Hausman test	2.2e-16	
Dependent Variable: MHDI_L		
T_LIGHT	0.2286	0.0425***
V_BF	0.02456	0.0112***
R^2	0.90	0.94***
Hausman test	2.2e-16	
Dependent Variable: MHDI_Y		
T_LIGHT	0.0819	0.0528***
V_BF	0.0105	0.0121***
R^2	0.64	0.78***
Hausman test	5.06e-05	

[a] ***: Significant at 1%

Results show that the MHDI is positively related to both explanatory variables, which is expected. Namely, the higher the level of electrification, the higher the MHDI is expected to be. The coefficient for electrification rate (T_LIGHT) is positive for all models and it is statistically significant at the 1% level. The results show that the electricity access sector is relevant for human development.

When assessing each HDI component separately, results show that the education component is the most affected by electrification, indicating that electricity plays a fundamental role in the indexes related to schooling. In other words, electricity access in the Brazilian rural area was closely related to the increase in the population's access to the education system. Although parallel educational policies are needed to increase MHDI_E, and it is not safe to say that electrification is the cause for this, electricity access is a major requirement to improve education. The assessment conducted by Kanagawa & Nakata (2008)confirm this influence. According to the study, which aimed to reveal quantitative relations between access to electricity and advancements in socioeconomic condition in rural Assam state, India, it is estimated that the literacy rate could rise to 74% from 63% with the electrification in the area.

The other two components of HDI – health and income – are statistically explained but not strongly influenced by the increase in the municipal electrification rate. Other explanatory variables may be more relevant in influencing these factors and should be tested. Or even, in the case of income, there should be a delay between electrification and income growth, being education perhaps the transmission channel for that. This means that labour productivity rises, due to education, to then cause income growth in the Brazilian poorest municipalities.

The Bolsa Família value variable coefficient (V_BF) is also positive for all models and it is statistically significant at the 1% level of significance. The results show that the program, which transfers income to families living in poverty and extreme poverty, does not have a large influence on the HDI. When analyzing the monthly values transferred per capita, the results can be better understood. On average each family served by the program received around BRL 26 per month. Thus, the program is more associated with the relief of hunger than with later stages of human development. It helps the extreme poor but has a small influence on HDI, since other factors need to be developed to increase the Municipal Human Development Index (MHDI), especially in its health and education components.

Final remarks

In 2003, Brazil launched the LpT program aiming to universalize access to electricity. The program focused on rural and isolated areas, also targeting to bring development to
2.6 the region along with electrification. With an initial target of reaching 10 million rural people until 2008, nowadays and after four phases, the program has reached almost 15.8 million people. The program is expected to continue until 2018.

LpT is considered the first electrification governmental policy that focused not only in guaranteeing electricity access to communities, but also in reducing social inequality in rural communities. The LpT program created a priority level based on social welfare parameters, such as HDI and electricity access inequality. Also, the program's execution along with other initiatives allowed electrification actions to be integrated to other governmental programs like Brazil Without Misery (Brasil sem Miséria, in Portuguese), Water for All (Água para Todos, in Portuguese), National Program for the Strengthening of Family Farming (Programa Nacional de Fortalecimento da Agricultura Familiar – PRONAF, in Portuguese), National Technical Assistance and Rural Extension Program (Programa Nacional de Assistência Técnica e Extensão Rural – PRONATER, in Portuguese), National Rural Housing Program (Programa Nacional de Habitacao Rural, in Portuguese), My House My Life (Minha Casa Minha Vida, in Portuguese) and University for All (Universidade para Todos, in Portuguese). In that way, the program could reach communities that were not covered by previous programs and foster sustainable development in those regions.

Regarding the achievements of LpT, it is important to evaluate the role of electrification in development goals. Electrification is expected to provide the means through which new jobs and income can be generated and welfare can be improved. The presence of electricity can be correlated with HDI, income improvement, educational and health access and with household's electrical appliances use. But, these benefits can only be reached if other complementary actions are executed alongside the electrification process. Electricity is key to development, but is not in itself a sufficient condition for achieving social development. The empirical results of this study showed that the education component of HDI was the one most influenced by electrification. Chances are that labour productivity growth (hopefully caused by education) will later generate income. But the analysis using the existing database is not able to indicate that yet. Also, development is a complex and multi-dimensional phenomenon, as such it requires a concerted, holistic approach based on complementary programs. These findings are very much in line with those from Slough et al. (2015), who also found that electrification efforts made by the LpT program were apparently more successful in higher HDI regions, implying that electricity access is more effective when accompanied by, or in addition to, other development-relevant policies and measures.

Despite the results achieved by the program, Brazil still has people with no access to electricity. Brazil is a continental country with areas that are hard to access due to the presence of large rivers and dense forests. Part of the population living in those areas are sparse, therefore, supplying electricity to these isolated communities is a challenge for the program. Another challenge is maintaining the affordability of electricity for low-income households benefitted by LpT after the end of the Program, which depend on cross-subsidies provided by the Brazilian interconnected electricity system, guaranteed only until 2018.

3 UNDERSTANDING THE MULTIDIMENSIONALITY OF ENERGY POVERTY IN BRAZIL

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This paper under revision by the authors and should be submitted to Energy Policy. Abstract

3.1 The different dimensions that characterize energy poverty can be assessed by a Multidimensional Energy Poverty Index (MEPI). This study adapts and calculates a MEPI for Brazil, contributing to understanding the evolution of incidence and intensity of energy poverty 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 access to modern energy fuels and in the ownership of some primary appliances, 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. There are still 11% of households living in energy poverty conditions and, in rural areas, this number reaches 16%. Considering the social and geographic heterogeneity of Brazil, we characterize energy poverty across different regions and socioeconomic groups. Results show that the isolated areas in the northern regions are the most deprived of energy services. We finally underscore the income inequality that is somehow related to situations of energy poverty. Non-energy poor families tend to have an income at least twice as high as that those families considered energy poor.

3.2 *Key words: energy poverty; energy services; multidimensional energy poverty index; Brazil*

Introduction

Guaranteeing access to affordable, reliable, sustainable, and modern energy services for all is an important challenge of this century. It has become a stand-alone goal of the 2030 Agenda for Sustainable Development and some of its Sustainable Development Goals (SDGs), e.g., Affordable and Clean Energy (SDG 7). Energy is critical for achieving decent living standards (Rao, Min and Mastrucci, 2019b) and satisfying basic human needs (Doyal and Gough, 1991). Assessments of the interlinkages between SDG 7 and other SDGs have highlighted energy's central role in achieving sustainable development (McCollum *et al.*, 2018), but in 2019, some 770 million people still lacked electricity, and 2.8 billion did not use clean cooking fuels (Energy Sector Management Assistance Program (ESMAP), 2020; IEA, 2020).

According to González-Eguino (González-Eguino, 2015), three alternative but complementary approaches focusing on energy access can measure energy poverty. These approaches consider that a person is energy poor if energy cannot be used due to technological, physical, or economic limitations. The technological approaches indicate that energy poverty is related to constraints in accessing modern energy fuels. The lack of connection to an electrical grid and the extensive use of biomass for cooking is central to the characterization of energy poverty in developing countries, where primary access to energy is a common problem (Pachauri *et al.*, 2004; González-Eguino, 2015; Dagnachew *et al.*, 2019). Lack of access to energy has been widely used as a proxy to measure energy poverty and has been defined in many different ways, depending on the context (Thomson and Snell, 2013; Bouzarovski and Petrova, 2015; González-Eguino, 2015; Mould and Baker, 2017; Mendoza *et al.*, 2019).

Beyond this form of understanding energy access and energy poverty, there are other ways of comprehending and framing this issue. For instance, when it comes to developed economies, structural access is no longer a major concern, and literature focuses on the affordability problem, using expenditure-based indicators to measure energy poverty (Pachauri *et al.*, 2004; Thomson and Snell, 2013; Meyer *et al.*, 2018; Sánchez-Guevara Sánchez *et al.*, 2020). In this sense, people are considered energy poor or fuel poor when there is an inability to pay for essential energy services (Waddams Price, Brazier and Wang, 2012; Romero, Linares and López, 2018; Randazzo, De Cian and Mistry, 2020). Threshold indicators, such as those based on expenditure or physical metrics, may overlook the complexity of energy poverty and its nuances, especially when social relations, norms, and behaviors shape how people benefit differently from access to energy services (Day, Walker and Simcock, 2016). Physical threshold or engineering-based approaches estimate a minimum level of energy consumption to fulfill basic needs (Pachauri *et al.*, 2004; González-Eguino, 2015; Ribas, Lucena and Schaeffer, 2017, 2019; Dagnachew *et al.*, 2019). The latter depends on many different parameters which are specific to other energy uses (Faiella and Lavecchia, 2019; Nico, 2020). However, these indexes hide several aspects of consumption on cultural and behavioral attributes that can be different at subnational levels and across different socioeconomic groups (Barnes, Khandker and Samad, 2011; González-Eguino, 2015).

A more comprehensive metric is required to understand energy poverty in all its components (Pachauri and Spreng, 2011; Day, Walker and Simcock, 2016) and multidimensional indexes include other dimensions beyond access and expenditure (Patrick Nussbaumer, Morgan Bazilian *et al.*, 2012; Audrey Berry, 2018). The Multidimensional Energy Poverty Index (MEPI), described by Nussbaumer et al. (Patrick Nussbaumer, Morgan Bazilian *et al.*, 2012), has been adapted to different research contexts and objectives (e.g., (Pachauri and Spreng, 2011; Patrick Nussbaumer, Morgan Bazilian *et al.*, 2012; Papada and Kaliampakos, 2016; Sadath and Acharya, 2017a; Romero, Linares and López, 2018; Fabbri, 2019; Mendoza *et al.*, 2019)). A recent development has led to the capability approach (Nussbaum and Sen, 1993), which accounts for the relationship between wellbeing and human development [19]. MEPI provides a comprehensive approach to identify multiple aspects in which a household is energy-deprived and the main features and determinants of energy poverty for a specific context (Sadath and Acharya, 2017b), helping to tailor and target policies (Kowsari and Zerriffi, 2011).

In some countries or regions, research on energy poverty still overlooks its multifaceted nature. For instance, the literature for Brazil focuses predominantly on the implications of access and availability on social dynamics or on the effects of national policies to eradicate the use of traditional fuels (Pereira, Freitas and da Silva, 2010; Giannini Pereira, Vasconcelos Freitas and da Silva, 2011; Mazzone, 2019b). However, the affordability dimension has received little attention (Gioda, 2019b), and studies have not explored energy poverty through the perspective of the energy services used. Even the recent literature on the multidimensionality of energy poverty in Brazil has not quantified the results (Mazzone *et al.*, 2021) or examined the situation across different regions, states, or income groups (Mazzone *et al.*, 2021; Pereira, González and Ríos, 2021).

Brazil is an interesting case study because initiatives have guaranteed access to modern cooking fuels and electricity for low-income families (Coelho *et al.*, 2018), with programs such as *Luz para Todos*[3], *Auxílio Gás*[4], *Tarifa Social*[5], and indirectly through *Bolsa Família*[6]. So far, Brazil has been successful in improving accessibility to electricity and to other modern fuels, like liquefied petroleum gas (LPG). However, in recent years, Brazil plunged into a severe economic crisis that ultimately led the number of people living under poverty and extreme poverty conditions to levels comparable to decades ago (IBGE, 2018), demonstrating that physical access to energy is only one aspect of reducing energy poverty and the widespread energy inequalities in the country (Piai Paiva, Jannuzzi and de Melo, 2019). This economic disruption, coupled with the rising prices of LPG, forced people back to using traditional, cheaper, and pollutant energy fuels, such as firewood, charcoal, and other collectible flammable materials for cooking (IBGE, 2020b; ANÍBAL, 2021; Felicio *et al.*, 2021). This situation sheds light on the persistent problem of energy poverty in the country and highlights Brazilian families' vulnerabilities, which go beyond solving the physical access problem. Such lessons are valuable to guide public policies that aim to eradicate energy poverty in a broader sense, not only in Brazil but in other countries that still face accessibility problems. Better understanding the broader context of energy-poor families helps design policies that have a higher chance of success (Papada and Kaliampakos, 2016). Beside understanding the overall situation of energy-poor households and their surrounding infrastructure (Aristondo and Onaindia, 2018b; Mendoza *et al.*, 2019), in countries characterized by large inequalities, it is also critical to identify the profile of the social groups that live under conditions of energy deprivation and are most likely to be pushed into energy poverty (Sharma, Han and Sharma, 2019).

This paper presents a comprehensive quantitative understanding of different dimensions of energy poverty in Brazil and their evolution over time. The Multidimensional Energy Poverty Index (MEPI) is adapted to the Brazilian case to quantify the number of energy-poor people (prevalence) and the intensity of this condition (severity). Considering the importance of social and regional heterogeneity within the country (PNUD, IPEA and FJP, 2016; IBGE, 2017a, 2018), we analyze results for different regions and socioeconomic groups. To our best knowledge, there is no previous literature assessing

[3] Luz para Todos is a program that aims to universalized electricity (Eletrobras, 2021a).
[4] Auxílio Gas were a social program established in 2002 that assist low-income families on the purchase of LPG through a bimonthly voucher (BRASIL Presidência da República, 2002).
[5] Tarifa Social is a discount on the electricity bill, provided by the Federal Government to registered low-income families (Ministério de Minas e Energia, 2021).
[6] Bolsa Família is an income direct transfer program, with the aim of overcome their situation of poverty and vulnerability (Caixa Economica Federal, 2021).

historical multidimensional energy poverty indexes in developing countries focusing on the heterogeneity across regions, income groups, and between urban and rural areas.

The remainder of the paper is organized as follows. Next section introduces the context of energy poverty in Brazil. Section 3 presents the research method and describes the MEPI methodology, dimensions, and the 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 energy poverty eradication in the country and a social-economic characterization of those families considered as energy poor. Finally, we conclude by highlighting the main findings of this study and possible directions for future research.

3.3 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, Freitas and da Silva, 2010; Giannini Pereira, Vasconcelos Freitas and da Silva, 2011; da Silveira Bezerra *et al.*, 2017; Mazzone *et al.*, 2019). Although physical access to modern fuels in Brazil is currently considered universal (GRUPO DE TRABALHO DA SOCIEDADE CIVIL PARA A AGENDA 2030, 2021), infrastructure and affordability issues still hinder the benefits from using modern fuels (Grottera *et al.*, 2018; Rao, Min and Mastrucci, 2019b; Mazzone, 2020b). The persistent use of firewood and charcoal for cooking is highly associated with household financial constraints (Gioda, 2019a). The affordability problem has been discussed since the 1970s, and different public policies (e.g., *Auxílio Gás*) tried to guarantee that all families could acquire LPG to substitute firewood for cooking. These policies were successful, but there have been no significant advances in this area since the 2010s, until finally in 2021 when the government launched a new LPG subsidy program. The ongoing use of firewood can be associated with the high LPG prices, which can reach 10% of minimum wage[7], and the lack of subsidies to support its use (Coelho *et al.*, 2018; Gioda, 2019b). This new program intends to complement social protection programs under the current context of high LPG prices observed in 2021. The *Bolsa Família* program aimed to guarantee that families could

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

afford a minimum basket of goods and services, including LPG, but the assistance value did not keep up with inflation and LPG price increases (Mazzone *et al.*, 2019). Recently, *Bolsa Familia* was discontinued and replaced by a new program called *Auxílio Brasil*, whose continuation after 2022 is still uncertain. Even though LPG is available for sale in almost every municipality in the country, low-income families still stack LPG with firewood for cooking (Coelho *et al.*, 2018), primarily because of budget constraints (Coelho *et al.*, 2018; IBGE, 2018)[8].

Electricity is available in 99.8% of all Brazilian households. In the last two decades, a successful policy to universalize electricity access in rural areas has been implemented (IBGE, 2020b). *Luz para todos* (LpT) connected 3.5 million households, bringing electricity access to approximately 16.9 million people (Eletrobras, 2021a). Despite these advances, there are still areas without access to electricity (Junior and Seabra, 2021), mostly remote areas, and there are issues regarding the quality of the service provided (ABR Energias Renováveis, 2020; GRUPO DE TRABALHO DA SOCIEDADE CIVIL PARA A AGENDA 2030, 2021). Moreover, people still face financial constraints to pay for energy services, and access to social security programs is not always guaranteed (Rao and Ummel, 2017; Grottera *et al.*, 2018). In 2010, the government created a program to subsidize electricity tariffs for low-income families and vulnerable groups. The *Tarifa Social* (TS) program offers discounts on tariffs for those registered in the *Cadastro Único*[9] 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% (Ministério de Minas e Energia, 2021). On average, a Brazilian household consumes about 165 kWh/month, far above the 30-kWh of the highest discount range, and low consumption levels usually occur in families that also lack other essential services, such as health and educational (Grottera *et al.*, 2018).

Both programs, LpT and TS, contributed to increases the average ownership of appliances to some extent (MDA Pesquisas, 2013b), though these trends are mostly attributed to economic growth and the expansion of other social programs, like *Bolsa Família*,

[8] There is, however, a cultural aspect of firewood consumption for cooking in some regions, which is not necessarily related to income (Mazzone, Cruz and Bezerra, 2021).
[9] Cadastro único is an instrument that identifies and characterizes low-income families. Since 2003, it is the main tool used by Brazilian State for the selection and inclusion of families in federal programs (Ministério da Cidadania, 2021).

observed in the first decade of the 2000s (Villareal and Moreira, 2016; Grottera *et al.*, 2018). Despite the increasing penetration of appliances in Brazilian households, ownership rates remain quite uneven, reflecting socioeconomic disparities. Some appliances, like washing machines and air conditioning, for example, are not present in all households and, in fact, are far from being present in most homes (Rao and Ummel, 2017; Grottera *et al.*, 2018). Brazil has a vast and heterogeneous territory. with significant differences across geographical regions in appliance ownership as well as in final energy consumption (IBGE, 2017a; EPE, 2019).

Methodological approach

3.4 Since the relevance of the different components that can give rise to a situation of energy poverty are context-specific, we first define what the critical dimensions of energy poverty in Brazil are. In this way, we can have a comprehensive quantitative understanding of different dimensions of energy poverty. Second, we gather the required data to measure the identified components. Lastly, we calculated the MEPI for whole country, as well as across regions, income groups, and place of residence according urban/rural conditions.

3.4.1 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 (Patrick Nussbaumer, Morgan Bazilian *et al.*, 2012). From this perspective, each dimension of the MEPI corresponds to a different energy use that meets a specific energy service, such as lighting, cooking, communication, food conservation, appliances for indoor thermal comfort, and others (Rademaekers, Koen, Yearwood, Jessica, Ferreira, Alipio, Pye, Steve, Hamilton, Anisimova *et al.*, 2016). 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 Nussbaumer, Morgan Bazilian *et al.*, 2012), each MEPI's dimension can be computed so as to characterize the incidence of deprivation in a society (H) as well as it's the intensity (A) (Patrick Nussbaumer, Morgan Bazilian *et al.*, 2012; Okushima, 2017; Mendoza *et al.*, 2019). Considering the Brazilian context and based on the MEPI literature (Patrick Nussbaumer, Morgan Bazilian and Yumkella, 2011;

Thomson, Snell and Bouzarovski, 2017; Meyer *et al.*, 2018; Mendoza *et al.*, 2019), we analyze three different dimensions related to (i) Physical Access, (ii) Appliances Ownership, and (iii) Affordability (Table 5). Each dimension can vary from 0 to 1, with 1 representing the highest degree of deprivation of energy service and 0 a situation of non-deprivation.

Physical access is assessed by two parameters: cooking, and electricity, the latter indicated by lighting services (Patrick Nussbaumer, Morgan Bazilian and Yumkella, 2011). If a household use LPG, natural gas, or electricity to cook, it is considered non-deprived (0); otherwise, deprived (1). The index for cooking deprivation includes only households that declare that use exclusively firewood and charcoal for cooking. The metric does not consider fuel stacking, a common practice in Brazil (Coelho *et al.,* 2018), that could be viewed as an important measure of energy poverty. Households that combine biomass with modern fuels for security reasons, or financial constraints, are captured by the Affordability dimension.

Regarding physical access, accessibility to electricity is the first step for a family to have different appliances and access to a wide range of energy services, and indeed electricity access is associated with many benefits for individuals and their communities (Kanagawa and Nakata, 2008; Kanti Bose, Uddin and Mondal, 2013; da Silveira Bezerra *et al.*, 2017). But not all electrical connections are reliable, which can restrict their use (Mazzone, 2019a; ABR Energias Renováveis, 2020; Pelz, Pachauri and Rao, 2021). We measure electricity access in terms of grid connection or availability of 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 context of Brazil, we identify as the most relevant parameters indoor thermal comfort, food conservation, and access to information, communication and entertainment (Patrick Nussbaumer, Morgan Bazilian and Yumkella, 2011; Mendoza *et al.*, 2019). Refrigerators or freezers have an important role in people's livelihood, as they allow for a variety of food types and the conservation of fresh food. These appliances are one of the first adopted by a household, as they offer an essential energy service (MDA Pesquisas, 2013a). 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, Uddin and Mondal, 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 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. Internet access was considered as its use at home or from a mobile phone.

Considering Brazilian hot and humid climate (IBGE, 2002), thermal comfort in relation to space cooling services is included as a dimension of energy poverty[10]. As a metric for thermal comfort, we consider the ownership of air conditioning (AC) appliances, with 1 capturing a status of non-ownership and 0 of ownership. Space cooling can be also obtained through the use of fans, but these appliances work best in a situation of hot and dry climate. Moreover, the energy requirements are much more limited compared to air conditioning, which instead is the appliance that has been associated more with cooling gaps (Mastrucci *et al.*, 2019b; Pavanello *et al.*, 2021). Since this energy service is most important in hotter climates, we weigh the ownership parameter by the normalized Cooling Degree-Days wet bulb (CDD_{wb}[11]) indicator, which we called CDD_{normal}. CDD_{normal} varies from 0 to 1, with 1 representing the hottest conditions observed in the country. The final parameter is obtained by multiplying AC ownership by CDD_{normal}. To calculate the CDD_{normal} weight for the space cooling parameter, we use data from (Mistry, 2019), which covers urban and rural areas and the States' capitals.

The third dimension, Affordability, makes it possible to capture situations of limited capacity to actually use energy services, because of economic conditions and financial constraints (Betto, Garengo and Lorenzoni, 2020). There are several expenditure-based indicators (Fabbri, 2019), and here we use a relative metric indicating that a family is considered energy poor (1) if the share of its energy expenses over total expenses is above a certain threshold. The threshold is twice the mean of the region's energy expenses in

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

[11] Cooling degree-days (CDD) is calculated by summing 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. CDDwb is measured considering humidity, for wet-bulb conditions (ASHRAE, 2009; Mistry, 2019).

which the household live. Energy expenses include electricity, gas, and other fuels used at home, but they do not include transport. Total expenditure considers all the collective costs related to a household plus individuals' expenses, such as transportation, health, travels, and others. As we intend to have a state-level analysis, the regional mean was calculated by state and urban/rural areas (**Error! Reference source not found.**). We choose not to use national means, as the use of energy depends on regional and cultural aspects (Rao and Ummel, 2017).

Table 5: Defined dimensions and their weights 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)	Do not have grid connection
Appliance's Ownership (ap) $w_{ap}=1/3$	Space Cooling (cl) $w_{ap(cl)}=1/9$	Cooling appliance ownership	CDD normal Has AC	Do not own (weighted by CDD normal)
	Information/Communication (i) $w_{ap(i)}=1/9$	Access to information	Has radio or TV	Do not own
			Has internet access	Do not own
	Food Conservation (f) $w_{ap(f)}=1/9$	Food conservation appliance ownership	Has refrigerator or freezer	Do 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 median

3.4.2 Data source

We measure the poverty indicators described in the previous section by using microdata on households expenditure patterns and characteristics from the main national household expenditure survey from the Brazilian Institute of Geography and Statistics in Brazil (Instituto Brasileiro de Geografia e Estatística, IBGE), the Pesquisa de Orçamentos Familiares (POF) [78]. We use the three latest waves, 2002-2003, 2008-2009, and 2017-2018, covering a period of more than 15 years during which the country has seen a significant structural changes [41,79]. The survey is based on a sample of approximately

50,000 households that represent all Brazilian homes. The questionnaires from the three waves contain information about household overall conditions, appliances' ownership, individuals' characteristics, and detailed income and expenses data. The analysis was made at the state level , differentiating between urban and rural areas.

3.4.3 Multidimensional Energy Poverty Index (MEPI)

We calculate the MEPI for Brazil considering a population of *n* individuals and *d* dimensions, being, 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 the POF's survey each year, and *j= {py, ap or af}*, as described in **Error! Reference source not found.**. Each dimension *j* is weighted equally, therefore, $w_{py} = w_{ap} = w_{af} = 1/3$. Within each of the three dimensions, parameters are also equally distributed. For example, cooking and electricity within the physical access dimensions are weighted 0.5 and 0.5, respectively.

For the individual i, c_i is a weighted sum index representing the energy poverty score condition of an individual. It is calculated as shown in Equation 4:

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

Equation 4

Where we defined:

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

Equation 5

An individual is defined as multidimensionally energy poor if her/his energy poverty score c_i is above a specific defined cut-off, $c_i \geq k$, where k is the deprivation cut-off, $0 < k < 1$. The final score $c_i(k) = c_i$, if $c_i \geq k$ and $c_i(k) = 0$ if $c_i < k$. The number of dimensions in which an individual is deprived can be identified by k as higher is k, more dimensions are included to considered energy poor households; when $k = 1$, the individual suffers from deprivation in all dimensions. We used the cut-off $k = \frac{1}{6} = 0.16$. In other words, a household is considered energy poor if it does not have at least one of the physical access parameters or lacks a combination of two appliances parameters

(Table 5). This definition chosen is based in the fact that a house should have a minimum of electricity of access to modern energy fuels for cooking.

Based on the above equations, we can define a multidimensional headcount ratio, H (Equation 6), which identifies the percentage of people considered energy poor according to the multiple dimensions considered in Table 5 relative to the cut-off defined:

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

Equation 6

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 $c_i(k)$:

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

Equation 7

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

$$MEPI \ = \ H \ x \ A$$

Equation 8

It is important to note that 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 Nussbaumer, Morgan Bazilian *et al.*, 2012). For that reason, we run a sensitivity analysis for k and w. We analyze different values for each variable.

A sensitivity analysis for the cut-off values was performed, varying k from 0.1 to 0.9. As closer k is from 1, less families are defined as energy poor. The sensitivity analysis for the weight values is based on the rank exponent method (Sadath and Acharya, 2017b), which allows to evaluate a range of combinations for w_j through an iterative approach for the three dimensions using different ρ values. For a certain number of 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 the equation 6 (Roszkowska, 2013):

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

Equation 9

The parameter ρ is used to describe weights distance, $\rho = 0$ results in equal weights. The higher is ρ; 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 ρ = 2, the dimension with the lowest weight became irrelevant (ANNEX 2).

Results for energy poverty in Brazil

3.5 3.5.1 Analysis of energy poverty's dimensions

Before examining the aggregate results for the MEPI index, we analyze the evolution of each dimension of energy poverty for the 2002-2018 period. From Figure 4, it is possible to notice 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 Appliances Ownership dimension. Over time, the Affordability dimension has not changed significantly, and energy-deprived households are mostly concentrated in rural areas.

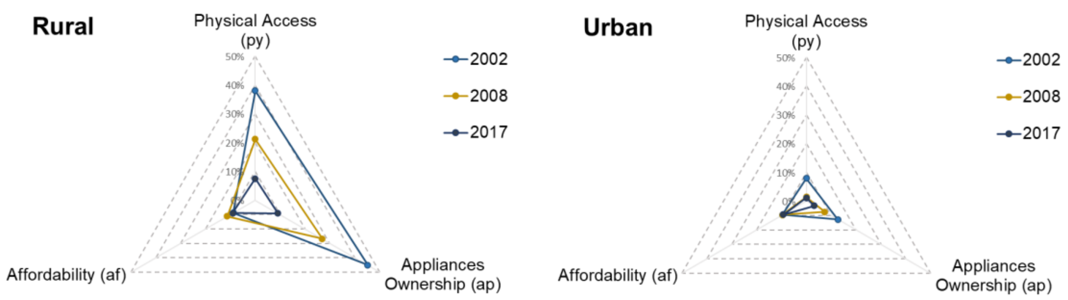

Figure 4: Evolution of Brazilian households deprived in the three dimensions of energy poverty - i) Physical Access; (ii) Appliances' Ownership; and (iii) Affordability (2002-2017). Percentages indicate the fraction of households in a situation of deprivation with 100% being the maximum level of deprivation

The lasting households, which accounted for 5.5% of rural households, deprived in the Physical Access dimension are primarily associated with the use of 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 Appliances Ownership dimension shows the greatest improvement over the analyzed period compared to other dimensions due to new electrical connections combined with the prosperous economic period in Brazil in the 2000s. Households deprived in Appliances Ownership dimension decreased from 2002 to 2017, both in rural and urban localities, falling, respectively, from 45% to 9% and from 13% to 3%, mostly due to the universalization of TV and refrigerators (MDA Pesquisas, 2013a). The growth in food conservation equipment ownership achieved 95% and 99% in rural and urban households, respectively. AC ownership rate also increased along the observed period. But, unlike TVs and refrigerators, ACs are still not widespread in Brazil.

Unlike the other two dimensions analyzed, the share of households deprived in the Affordability dimension was kept constant, around 9% throughout the assessed period. Energy demand economic cycles and the evolution of fuel prices compared to those for other goods influence the energy expenses of a family (ABR Energias Renováveis, 2020).

It is important to notice that there is a high degree of heterogeneity in all dimensions of energy poverty in Brazil, reflecting the differences observed across regions and income deciles[12]. From a regional perspective – Figure 5 –, the North and Northeast regions started 2002 with the highest incidence of deprivation in the Physical Access and Appliances Ownership dimensions, which were significantly reduced through 2017. As a result, from 2002 to 2017 the Affordability dimension, which stayed almost constant over the years, became the largest contributor to energy poverty in these regions.

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

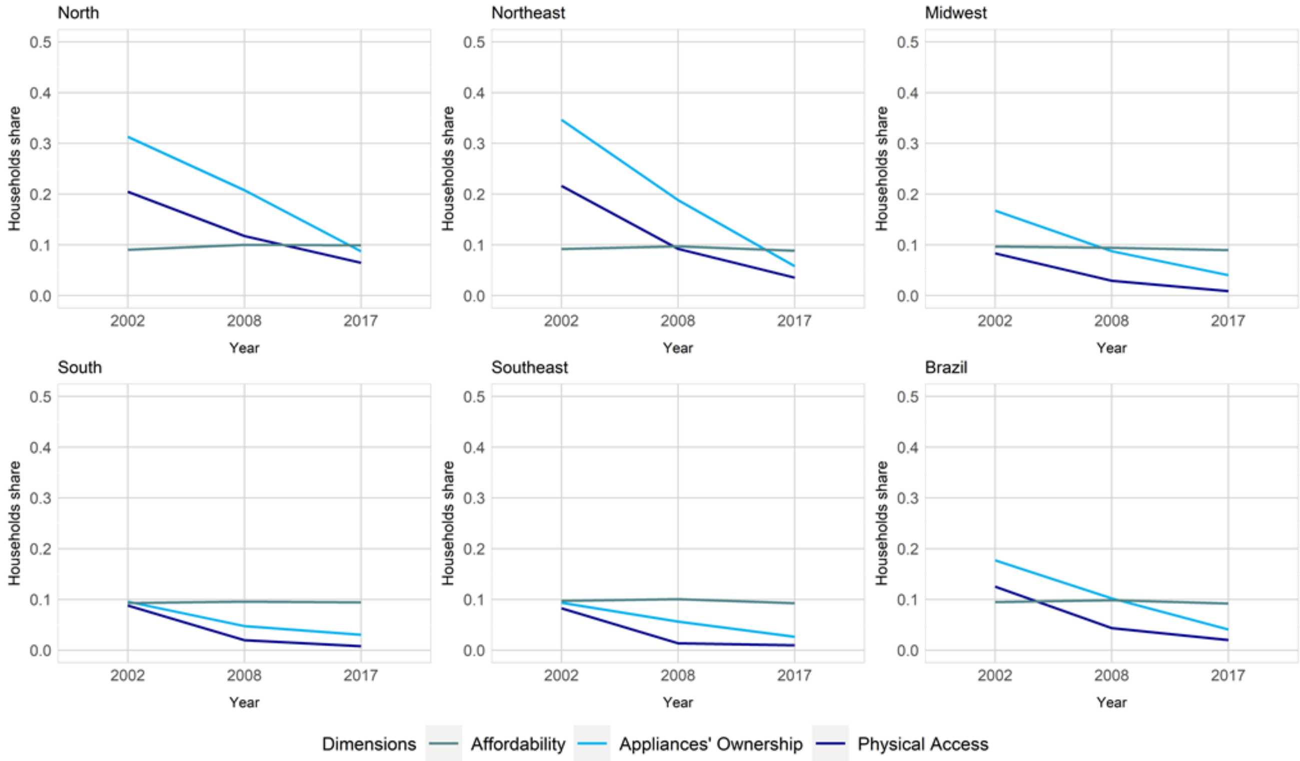

Figure 5: Dimensions analysis index results by region (2002-2018).
Note: N= North, NE: North-East, MW: Midwest; S: South, SE: South-East.

The high level of deprivation in the Physical Access and Appliances Ownership dimensions in the North and Northeast explain why, in 2002-2003, these regions had the lowest population deprived in terms of the Affordability dimension. First, it is necessary to have physical access to energy for a family 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 Appliances Ownership, but did not improve the Affordability dimension. Since the Affordability dimension is assessed in relative terms, it is not very sensitive across regions and rural/urban conditions (Figure 5), like the other dimensions. More about the heterogeneity of the results can be seen in ANNEX 4. Overall, the improvements observe for the Physical Access dimension are highly associated with the decrease of biomass consumption, except in the North and Midwest regions, where advances in electricity access were the main reason for the improvements observe. Also, most households deprived in the Physical Access dimension are from rural areas. As for electrical connection, the deprivation is concentrated in the North region, and it is not significant in the other regions.

In 2017-2018, while 1% of households did not have access to electricity, 3% complained about irregularities in power supply, declaring that the service is available only for a few hours a day or has constant cut-offs . Problems are most frequent in rural areas from the North and Midwest regions, reaching 22% and 9% of total households, respectively. Although this is not reflected in the MEPI, future research should also consider the quality of the service.

Besides regional differences, income distribution has a significant influence on energy poverty conditions according to the dimensions analyze here, endorsing previous studies (Sanches-pereira, Gustavo and Teixeira, 2016; Coelho *et al.*, 2018; Grottera *et al.*, 2018; Gioda, 2019a). In 2017-2018, Physical Access deprivation in urban households was concentrated only in the first two deciles (Figure 6). The same is observed in the Appliances Ownership dimension. 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. Deprivation in this dimension is dependent on the existence of energy access and the electrical appliances used at home.

Our results reveal households' inability to pay for LPG in isolated rural areas. The distribution of LPG reaches almost all municipalities, but higher prices combined with low incomes lead to the use of firewood in these locations (Giannini Pereira, Vasconcelos Freitas and da Silva, 2011; Mazzone *et al.*, 2019). Although there is a cultural aspect for the continued consumption of firewood (Mazzone, Cruz and Bezerra, 2021), this result is mainly related to financial constraints (Coelho *et al.*, 2018; IBGE, 2018).

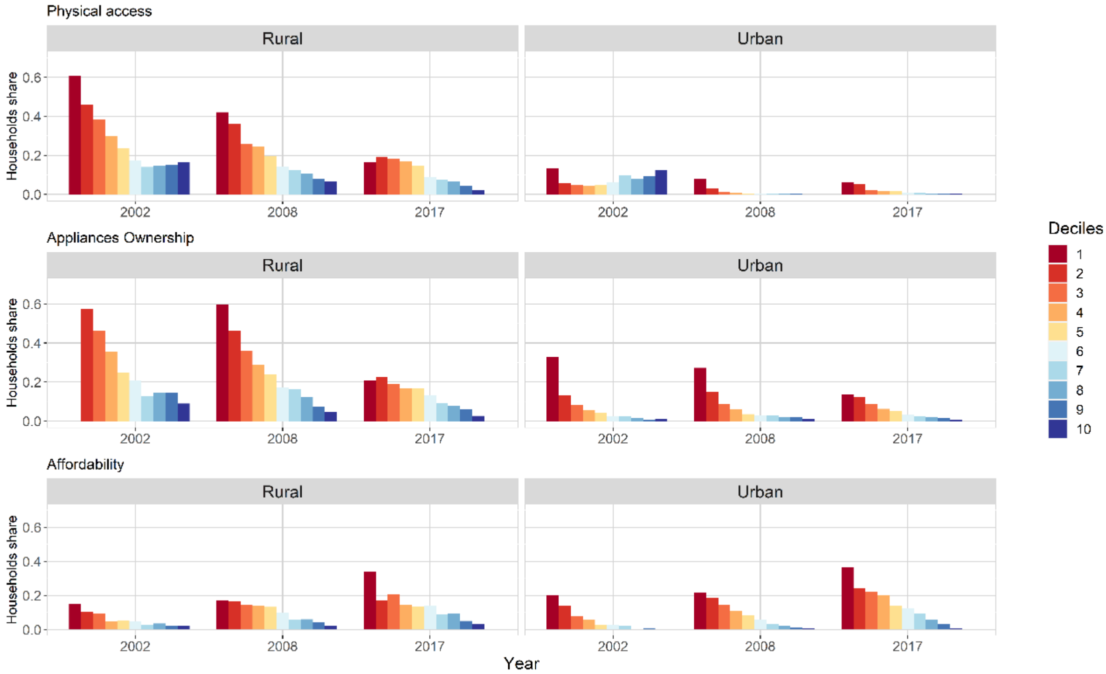

Figure 6: Household share according to the three dimensions of energy poverty by income deciles and rural/urban situation in Brazil (2002-2018)

For the Appliances Ownership dimension, the difference in the deprivation rate between the first and tenth decile is not so significant. This is due to the high presence of both TV and refrigerator in most households. On the other hand, income is not the only factor that influences the AC ownership, being also largely dependent on outside temperature (Depaula and Mendelsohn, 2010). The higher ownership rates for this equipment are in the urban areas of the North region, the hottest in the country, reaching an average of 38% of families and 85% of households on the tenth decile.

Interestingly, the income heterogeneity observed in 2002-2003 and 2008-2009 for the Physical Access and Appliances Ownership dimensions were not maintained in 2017-2018. In this later period, the differences between the first and tenth decile are mostly for the Affordability dimension. In fact, Affordability is only an issue after there is no deprivation in the other dimensions. Energy expenditure accounts for a large part of total expenses for low-income families. The wealthiest families (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%. As a result, more than 30% of families in the first decile are deprived in this dimension.

It should be noted that the metric used here does not discuss individual and cultural aspects of energy use. For that, it captures families considered deprived in all dimensions, even within the highest deciles.

3.5.2 MEPI

Combining the incidence (MEPI_H) and intensity (MEPI_A) of energy poverty, we calculated the MEPI for the Brazilian case study from 2002-2018. Results show a substantial reduction in energy-poor families in all regions (Figure 7). On average, in 2017-2018, 10.5% of households were classified as energy poor. When considering only rural homes, this percentage reaches 17%. Physical Access and Appliances Ownership improvements have lifted 30.7% of rural households out of the energy poverty situation between 2002 and 2017.

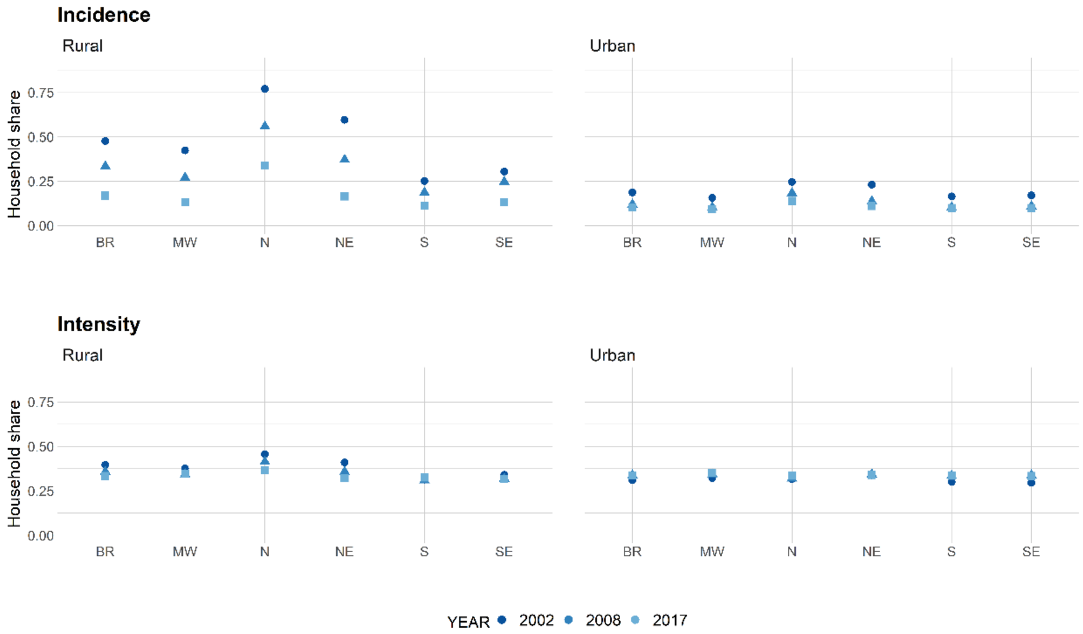

Figure 7: Measure of Incidence and intensity of energy poverty on the period observed (2002-2017)

Following the results for each dimension, the North 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. Overall, rural households tend to be more energy poor. The lowest rate of energy poverty is observed in urban areas of the Midwest region.

It is interesting to observe that the energy poverty intensity has not changed significantly since 2002. Intensity is calculated as an average of deprivation index, di, for households defined as energy- poor. Results show that energy-poor families maintained the same level of deprivation over time. On average, intensity went 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 North and Northeast regions also have the highest values for energy poverty intensity. For rural areas of the State of Amazonas, intensity reached 0.402 in 2017, the highest observed at the State level (ANNEX 5).

Figure 5 presents a map of the results for MEPI for the different Brazilian States, which clearly shows 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; in other words, it reflects 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 since 2002. The map shows a major role for the Affordability dimension of energy poverty in 2017-2018, reflecting a lower heterogeneity at the regional level (Figure 5).

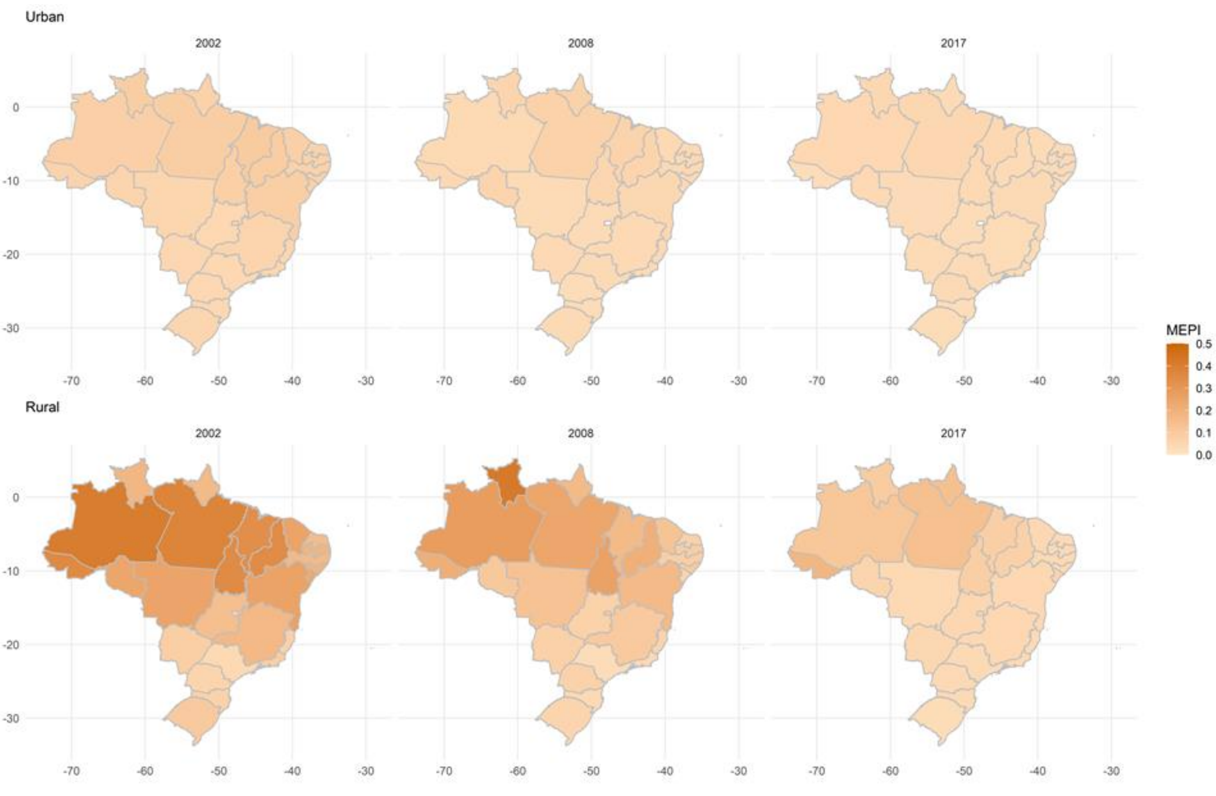

Figure 8: Brazilian map of MEPI index (Incidence x Intensity): States level over the period 2002-2017

As discussed previously, results can vary across income levels. As expected, when we observe the results by decile, the incidence of energy poverty is predominant in low-income households (Table 6). In 2017-2018, MEPI_H reached around 44% of first decile's households, against less than 2% in the tenth. 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.

Table 6: Average results of MEPI and its 67omponentes (MEPI_H and MEPI_A) by income decile according to the last POF wave observed, 2017-2018

	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

3.5.3 Sensitivity analysis

MEPI index is very sensitive to the choice of dimensions, their weights, and the cut-off values (Patrick Nussbaumer, Morgan Bazilian *et al.*, 2012; Pelz, Pachauri and Groh, 2018). For that reason, we run some sensitivity analyses based on different cut-off values and weights composition.

For the cut-off, k, sensitivity values varied from the $k = 0.1$ to 0.9, for the 2017 MEPI values. An increase in k means that a household must be deprived in more dimensions to be in energy poverty. The higher is k; the fewer households are 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. Families deprived in all dimensions can be identified when $k > 0.9$. Absolute energy poverty is currently not commonly observed in Brazil, albeit there may be a deprivation of specific services. Still, only a small number of families are deprived in all dimensions, all of which are in rural areas of the North and Northeast regions, namely the States of Amazonas, Pará, Piauí, and Maranhão (ANNEX 6).

The number of households identified as energy poor is significantly lower when we consider $k > 0.3$ compared to the baseline $k = 0.16$ (Figure 9). Rural North is the only area that still has high values of energy poverty incidence when $k = 0.5$ (when deprived in half of the parameters). Intensity of poverty is not as sensitive to the cut-off changes. This is because we measure MEPI_A as an average of all households with $di \geq k$.

Overall, MEPI is not significant in Brazil when $k > 0.3$ for urban and for $k > 0.5$ in rural areas (Figure 10**)**.

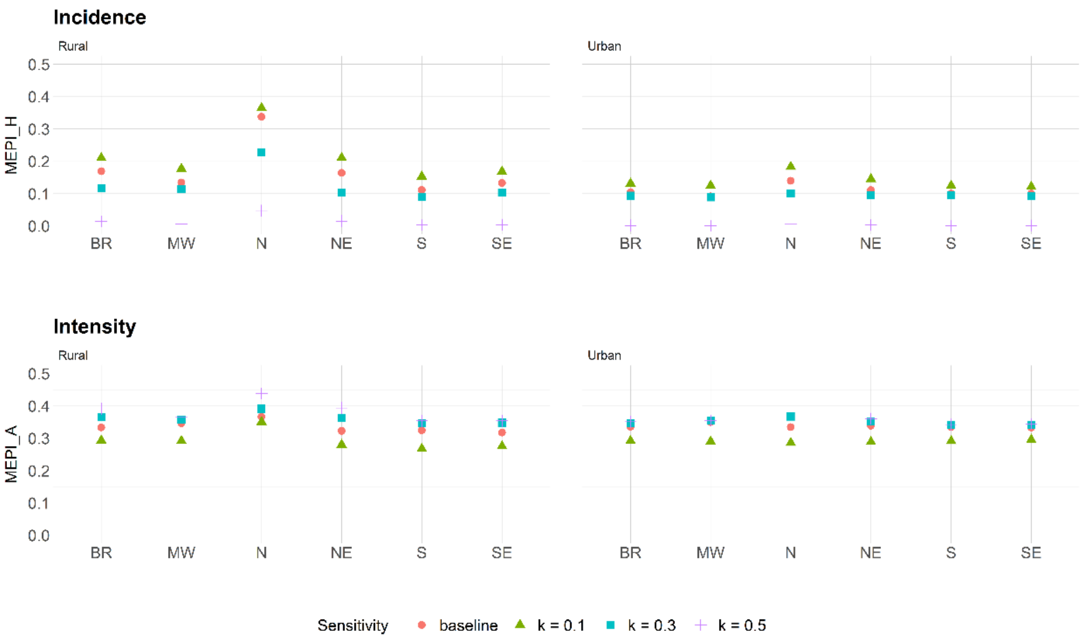

Figure 9: Incidence (MEPI_H) and Intensity (MEPI_A) of energy poverty for 68iferente cut-off (k) values for 2017-2018 period

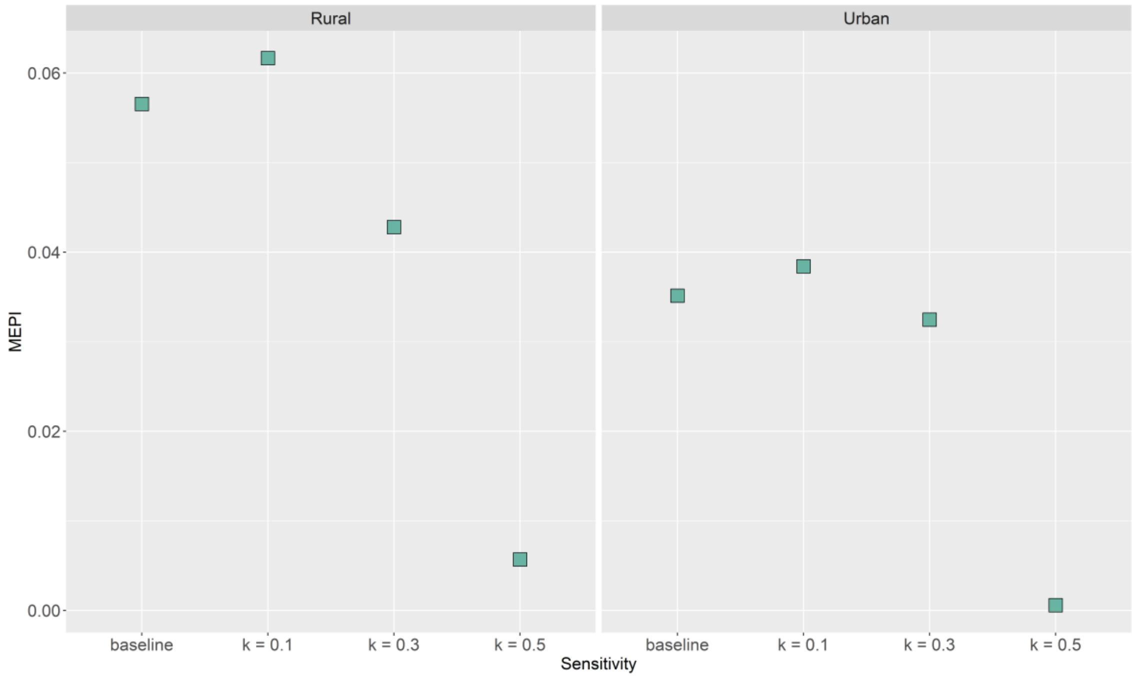

Figure 10: MEPI values in 2017-2018 for 69iferente cut-off (k) values

In addition, we compute different MEPI_H values for various combinations of weights. Figure 11 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 AC appliances ownership access is currently the primary service deprivation in the country. Minimum values are found for w_py = 0.64, w_ap = 0.29 and w_af = 0.07.

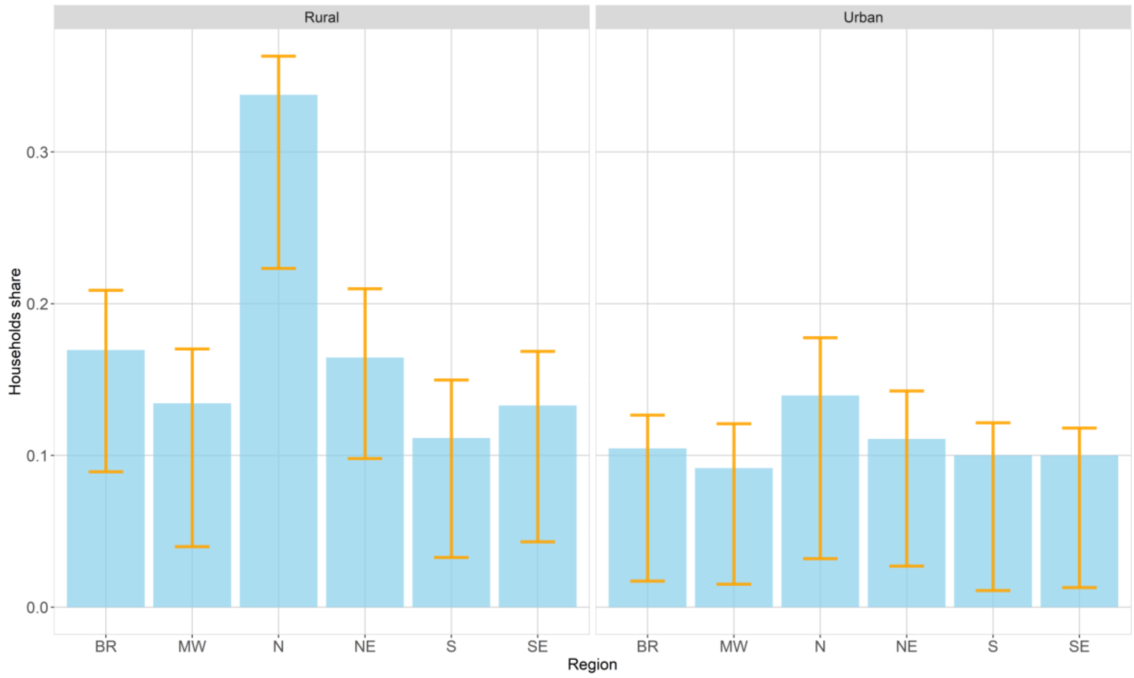

Figure 11: Dimension's weights sensitivity results by region for 2017-2018 period

Results from the sensitivity analysis do not change the overall conclusions. The same inequalities are observed. Rural households located in the North and Northeast regions remain with the highest values of MEPI_H, and low-income households are the mostly deprived in all situations.

3.6 Discussion

The main objective of this work is to have a comprehensive understanding of energy poverty in Brazil over time. For that, this section closely analyzes and correlates the observed results, focusing on the heterogeneities noticed at the regional and income levels. In addition, to better understand the context in which an energy-poor household is inserted, we also briefly analyze the overall living conditions of those identified as energy poor.

3.6.1 Important aspects of energy poverty in Brazil

The regional disaggregation used to measure energy poverty through MEPI corroborate with Brazil's geographical heterogeneity for other indexes like HDI and income poverty (PNUD, IPEA and FJP, 2016). While the country has, on average, 11.4% of its population living in energy poverty conditions, regional results vary from 9.7% in Midwest to 18.5% in the North, reaching 33.8% in the rural North. Physical Access and Appliances Ownership dimensions contributed the most to this result.

MEPI also translates social inequalities. As expected, poor households of rural areas had the highest values of MEPI. Furthermore, the use of biomass for cooking is more frequently observed in the lowest income groups, and the affordability problem is identified as the leading cause for that disparity.

The Affordability dimension showed the largest variation among income deciles. Our historical analysis shows that families 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 (Figure 6). Only when there are lower levels of Physical Access and Appliances Ownership, there is a high share of households with Affordability deprivation. From that, we can assume that Brazil is following the trend of developed countries in terms of energy poverty concerns, where the capacity to pay for energy is the major problem.

Overall, there is a persistent level of deprivation in the affordability dimension, indicating that programs like *Bolsa-Familia* and *Tarifa Social* were not sufficient to ensure lower energy expenses and lift families out of energy poverty. This corroborates with previous studies (Coelho *et al.*, 2018; Mazzone *et al.*, 2021). In addition, half the Brazilian households declared arrears on water, electricity, or natural gas bills. The problem is especially relevant in the North region, also corroborating previous findings (Piai Paiva, Jannuzzi and de Melo, 2019).

The high share of energy expenses can put families on the verge of energy vulnerability, where variations in energy prices and economic downturn can lead to energy poverty (Pereira, González and Ríos, 2021). For example, households' arrears with electric bills increased in the last year due to the COVID-19 recession (Rosa, 2021). Moreover, an increase in the use of solid fuels for cooking has been observed, even in urban areas, likely to be caused by increasing LPG prices (ANÍBAL, 2021). This shows that further refinements of the definition of energy poverty which are solely based on the Physical access dimension could help to identify circumstantial energy poverty. The likelihood of households' inability 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. 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.

Following the trend observed for the Physical Access dimension, appliances ownership also showed a relevant growth. Most families have at least the essential electrical equipment, TV, and refrigerator, purchased after the electricity access and economic improvement observed in the last decades. The use of such basic appliances is essential to improve living standards (Rao, Min and Mastrucci, 2019b).

Among the appliances considered in this study, AC was the only one far from universal use in the country, significantly influenced by region and income level. North and Northeast 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). Considering climate change scenarios for Brazil, AC ownership will be an important asset to prevent losses in wellbeing (Mastrucci *et al.*, 2019b; Bezerra *et al.*, 2021). For being one of the most common solutions for high temperatures, the use of AC is expected to grow significantly in the following years (EPE [Empresa de Pesquisa Energética], 2018). For that, future studies should pay more attention to the thermal comfort parameter and the role of AC ownership on energy poverty metrics.

The same is valid for internet access, which plays an important role in education (UNESCO, 2003). Although it depends on the telecommunication infrastructure, it can also be regarded from an energy service perspective. The presence of the internet in households is increasing rapidly, and it is highly associated with the widespread use of mobile phones. A redefinition of the internet parameter within the appliances ownership dimension should be considered, given its high importance, as more information becomes available with future surveys.

Intensity of energy poverty is very sensitive to the cut-off values used in the MEPI calculation. Even showing a decrease in the years observed, the variation is less significant than those observed on the incidence metric. Also, the sensitivity analysis indicates that the dimensions chosen and their weights highly influence MEPI, showing that this method is highly dependent of the researcher approach, whichcan be a limitation of this method(Patrick Nussbaumer, Morgan Bazilian *et al.*, 2012; Pelz, Pachauri and Groh, 2018; Pelz, Pachauri and Rao, 2021). Nevertheless, the main results in terms of the distributional situation of energy poverty across regions and income groups in Brazil remained valid.

3.6.2 Energy poverty and living surrounding conditions

By categorizing energy poverty according to some features of the households and individuals, we validate the statement made in previous studies that energy poverty is a contextual issue, which is interlinked with other deprivation conditions. To understand how conditions of energy poverty are more often observed under certain circumstances, we identified the most vulnerable groups according to different geographical, infrastructure, and social characteristics, which could be very helpful for the design and targeting of policies.

The variables observed were chosen considering existing literature on energy poverty and minimum requirements for decent living (Rao, Min and Mastrucci, 2019b; Vine, 2020). Data from POF (IBGE - INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA, 2018) provide information about households' characteristics and their surrounding infrastructure situation. House conditions contain information regarding natural lighting and reduced living spaces, while house structure is related to the presence of roof leakages, humidity, and deteriorated materials. As for the surrounding infrastructure, data provides information about the existence of paved streets, potable water supply and sanitization. We acknowledge that other dimensions may influence the severity and consequences of energy poverty, such as geography (Bouzarovski, 2014) and urban planning (Sánchez-Guevara Sánchez *et al.*, 2020), which are not considered here.

The data shows that the overall living conditions of energy-poor households are significantly worse than non-poor, regarding both the house attributes and the general surrounding situation (Figure 12). Also, the lack of surrounding public infrastructure in Brazilian rural areas – the gap between rural and urban areas regarding access to paved streets, water supply and sewage is much larger than the difference between other house attributes (household conditions and infrastructure). The lack of essential infrastructure can be correlated to the higher incidence of deprivation in physical energy access, while house characteristics are more related to the family monetary constraints. As stated in previous studies, there is a correlation between the living conditions and energy poverty situation(Sambodo and Novandra, 2019; Bhattacharya, Inekwe and Yan, 2021). The household's condition is often used as a dimension to obtain energy poverty of a country (Aristondo and Onaindia, 2018b), as it can be related to the building's energy efficiency, especially for indoor thermal comfort related issues(Gillard, Snell and Bevan, 2017; Pérez-Fargallo *et al.*, 2020). Also, household overall conditions can be correlated with monetary poverty conditions, that also is a cause for energy poverty(Rao and Pachauri, 2017; Paudel, 2021).

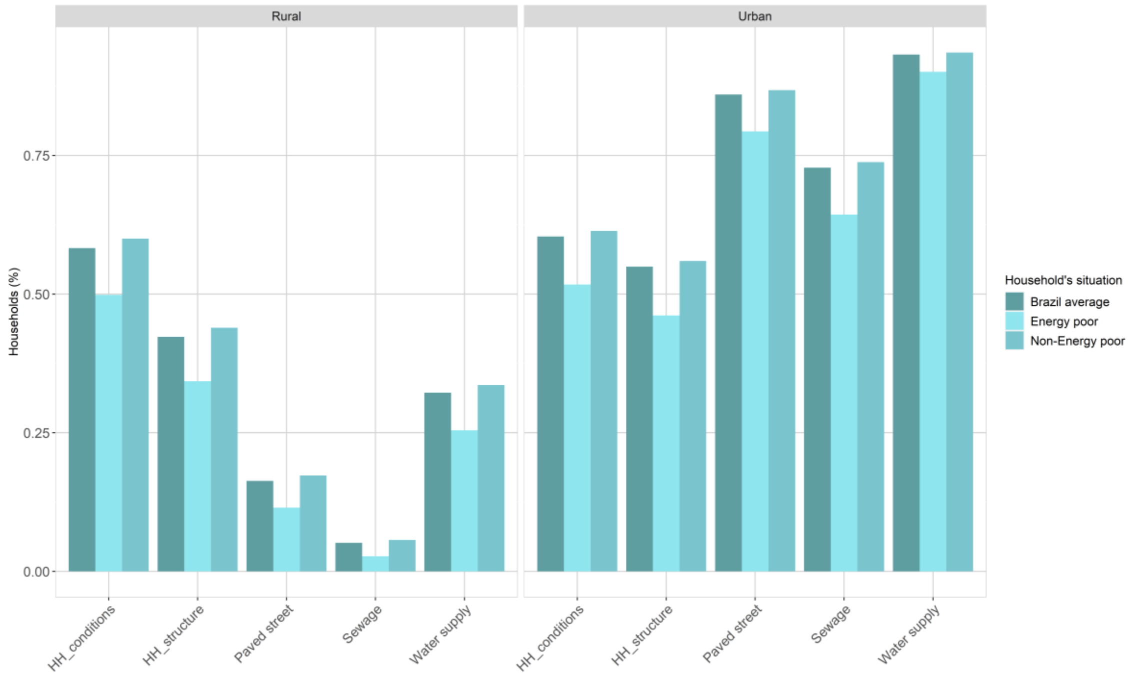

Figure 12: Household overall living conditions considering its energy poverty situation

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. Large distances and the lack of affordable public transportation between towns and villages escalate the cost of food and essential goods (including LPG and transportation fuel) to the local population, deepening economic and social inequalities (Mazzone, 2020a). The average cost of an LPG canister (13kg) in the State of Amazonas can be 26% higher than in the state of Rio Grande do Sul (ANP, 2021).

Similarly, Amazonian citizens pay 18% more to purchase diesel oil compared to those living in the southern states of Rio Grande do Sul and Paraná. Future research to further understand 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. The use of an energy poverty metric contemplating the transportation dimension should be considered in future studies.

In addition, women and children pay the highest price for lack of public infrastructure and geographical isolation (Leavens, Kennedy.M & Anderson, 2011; Figart and Warnecke, 2013; Parikh *et al.*, 2015). Research in the Global South shows how the lack of public infrastructures such as water provision, public lighting, and paved roads are linked to increased gender inequality in terms of time poverty, health, and an increased risk of gender-based violence (Pommells, 2015; Sommer *et al.*, 2015; Series, 2018).

One other aspect that we assess if differences in household head's characteristics, including gender, race, and literacy (Table 7). For gender, more differences were observed when comparing urban versus rural than the status of energy poverty. Nevertheless, in urban areas, it is possible to notice that energy poverty is more frequent in women-led households. Furthermore, energy poverty is most probable in households with non-white and non-literate heads of the family. These results are not surprising, given the high incidence of gender and race inequality in Brazil. Black and mixed-race people in Brazil account for the highest percentage of unemployed and are the most vulnerable in finding and keeping an occupation (IBGE, 2019a). Also, structural patriarchy contributes to high gender pay gap, job security, and a scarcity of women in the position of decision-making and leadership in the country (Pietropaoli and Xavier Baez, 2020).

It is not surprising that women and the black, multi-racial and indigenous communities in Brazil are more affected by energy poverty, given their isolated economic situation. Before the Covid-19 pandemic, in 2019, Brazil's black and mixed-race people 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 the gender dimension, which is still persistent in Brazil (Simões and Matos, 2008; Pietropaoli and Xavier Baez, 2020).

Finally, we also assessed information about the household's economy, in terms of average income, arrears on utility bills[13], *Bolsa-família* beneficiaries, and constraints to pay for food[14]. **Error! Reference source not found.** 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 has a significant difference to those non-poor, especially in urban areas. Energy poverty affects more the recipient of the social program *Bolsa-Família*. Also, between 24% and 34% of families that declared food deprivations are identified as energy-poor – for urban and rural, respectively – against 15% and 22% non-energy poor.

Table 7: Monetary conditions and characteristics of household's head according to the energy poverty situation

			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 (% 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)	Urban	0.54	0.65	0.52
	(% households)	Rural	0.66	0.75	0.64
	Sex (76oman)	Urban	0.44	0.49	0.43
	(% households)	Rural	0.31	0.30	0.31
	Non-literate	Urban	0.13	0.22	0.12

[13] IBGE survey, questionnaire about life conditions on POF 2017. Question: During the reference period of 12 months, due to financial difficulties, has your family delayed payment for water, electricity, or gas?

[14] According to 2017 POF's survey, we considered food deprived those families that answer *Yes* on variable V6109 of Life Conditions questionnaire: "In the last three months, did the food run out before the residents of this household had the money to buy more food?" (IBGE - INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA, 2018)

(% households)	Rural	0.31	0.38	0.29

The results for households that declared arrears on utility bills contrast with the other variables described above. When observing energy poverty according to delays in payment of the bills, we found that non-energy poor households are most frequently in debt than poor ones. This could indicate that people not identified as energy poor are at the limit of affording essential energy services and, therefore, in an energy vulnerability situation. Moreover, late payments for services can indicate budget constraints and a probable situation where families need to choose energy rather than other goods.

3.7 Conclusions

To design effective policies, it is crucial to evaluate energy poverty over time (Aristondo and Onaindia, 2018a; Alem and Demeke, 2020). For large countries, a broader analysis requires the characterization of energy poverty over time and the understanding of its geographical distribution (Gouveia, Palma and Simoes, 2019). Since Brazil particularly has a vast territory and a large gap between living conditions in urban and rural areas (IBGE, 2018), any historical analysis of energy poverty must comprehend the distinct situation across the country.

This paper has analyzed the energy poverty situation in Brazil for three different periods, 2002, 2008, and 2017. We went beyond the classical unidimensional metric and incorporated the concept of energy deprivation according to the final service demanded, using MEPI. By applying a multidimensional index in a historical analysis of energy poverty in Brazil, we explored how deprivation of energy services changed through time across different regions and income deciles.

Between 2002 and 2008, there were different policy efforts to guarantee access to modern energy sources, especially in rural areas. This, aligned with a prosperous economic cycle, contributed to the decrease in the number of energy poor households. The subsequent period also observed a reduction, albeit less intense, showing a slight saturation of the benefits from the physical access improvements and ownership of essential appliances in urban areas, also impacted by an economic slowdown.

Overall, MEPI in Brazil showed significant improvements in the period observed. Despite the improvements observed, Brazil currently has 11% of its population living in energy poverty conditions. In urban areas, this is due mainly to affordability restrictions. In rural areas, where 16% of all households are still considered energy poor, all dimensions contribute to the results observed. Intensity reduction was not as significant as incidence, meaning that energy-poor households are equally deprived in 2017 than they were in 2002.

To design policies to eradicate energy poverty it is important to have good metrics to identify energy-poor people and understand the determinants for this situation (Pachauri and Spreng, 2011; Patrick Nussbaumer, Morgan Bazilian *et al.*, 2012). Our study brings together some important lessons for policies to eradicate energy poverty in Brazil and other countries.

Mostly, the analyses show that physical access to energy was not enough to reduce the deprivation of essential energy services. Expenditure on energy still represent a high share of the household's total expenses. The inability to pay for energy or buy new and efficient equipment can lead families back to the use of biomass for cooking or not meeting thermal comfort needs. Governmental efforts like *Bolsa Familia* and *Tarifa Social* did not provide sufficient means to change the ratio of low-income families' energy expenditure to total income, which remained almost constant through time.

People who suffer from energy deprivation are more likely to be disadvantaged in overall infrastructure conditions. Joint efforts which strengthen infrastructure along with energy affordability programs should reduce energy poverty in deprived areas. We suggest that further adjustments to current governmental programs should be considered to reduce energy poverty. In addition, it is necessary to observe future trends and risks of energy poverty, including electricity reliability, thermal comfort needs and internet access.

4 IMPACTS OF A WARMER WORLD ON SPACE COOLING DEMAND IN BRAZILIAN HOUSEHOLDS

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Abstract

4.1 Air Conditioning (AC) appliances are a highly effective adaptation strategy to rising temperatures, thus making future climate conditions an important driver of space cooling energy demand. The main goal of this study is to assess the impacts of climate change on Cooling Degree Days computed with wet-bulb temperature (CDD_{wb}) and household space cooling demand in Brazil. We compare the needs under three specific warming levels (SWLs) scenarios (1.5°C, 2°C and 4°C) to a baseline with historically observed meteorological parameters by combining CDD_{wb} projections with an end-use model to evaluate the energy requirements of air conditioning. The effects of the climate change were isolated, and no future expansion in AC ownership considered. Carbon dioxide (CO_2) emissions associated with AC energy demand are also calculated. Results show an increase in both average CDD_{wb} and AC electricity consumption for the global warming scenarios in all Brazilian regions. The Northern region shows the highest increase in CDD_{wb} (187% in CDD_{wb} for SWL 4°C), while the Southeast presents the highest AC energy consumption response (326% in the AC energy consumption for SWL 4 °C) compared to the baseline. At the national level, CDD_{wb} and the AC energy consumption in all SWLs scenarios grow by 70%, 99% and 190%, respectively.

Keywords: climate change impact; climate change adaptation; energy cooling demand; household sector; cooling degree days; Brazil

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[15] BEZERRA, P.; DA SILVA, F.; CRUZ, T.; et al. Impacts of a warmer world on space cooling demand in Brazilian households. Energy and Buildings, v. 234, p. 110696, 2021. Available at: <https://linkinghub.elsevier.com/retrieve/pii/S0378778820334824>.

Introduction

Space cooling is the fastest growing energy use within the building sector, a sector that accounted for around 28% of total global energy-related carbon-dioxide (CO2)
4.2 emissions and for approximately one third of global final energy use in 2018 (IEA, 2019). In emerging economies, such growth is mostly associated with rising incomes (IEA, 2018), but also due to high temperatures and prolonged heat waves (IEA, 2018). Thus, the potential increase in demand for space cooling, which has grown by more than three times between 1990-2018 (IEA, 2019), is a critical energy issue.

The use of space cooling technologies is an autonomous form of adaptation available to households and workers to minimize climate change impacts and maintain comfortable temperature levels at homes and workspaces. Air conditioners (ACs) for indoor cooling are relatively low-cost and a highly effective adaptation strategy (IEA, 2018). However, adaptation to climate change through the use of cooling appliances will increase energy consumption and, depending on the energy mix, leading to higher GHG emissions (Hallegatte, 2009; Li, Yang and Lam, 2012), initiating in this way a positive feedback loop further amplifying future needs for adaptive measures (Barnett and O'Neill, 2010; Depaula and Mendelsohn, 2010). Therefore, analyzing the consequences of temperature increase on energy demand is extremely important to determine possible climate change mitigation and/or adaptation interactions, as well as to enhance energy demand forecasts (IPCC, 2014). Furthermore, the use of more efficient cooling technologies could considerably reduce the energy consumption associated with increasing temperatures (Davis and Gertler, 2015). In this regard, policies to promote energy efficiency of AC appliances are important to build a sustainable future (van Ruijven, De Cian and Sue Wing, 2019) and are object of new studies (Vieira, Nogueira and Haddad, 2018; Karali *et al.*, 2020).

There are different approaches to analyze the effect of ambient air temperature on energy consumption. Numerous studies have explored the use of the Cooling Degree Days (CDD) indicator to understand the possible impacts of increased air temperature on cooling energy demand in buildings (W.Y.Fung *et al.*, 2006; Daioglou, van Ruijven and van Vuuren, 2012; van Ruijven, De Cian and Sue Wing, 2019). CDDs are defined as the cumulative sum of the positive differences between daily mean ambient air temperature and a base threshold temperature over a certain time period (e.g. month or year) (Owen, 2009). Although this indicator does not consider climate parameters such as solar irradiation or parameters regarding the building's envelope and type, it is commonly used as a proxy to calculate space cooling energy demand to maintain thermal comfort levels in residential and commercial buildings (Atalla, Gualdi and Lanza, 2018; Mistry, 2019). Some studies have applied top-down approaches, in which CDD data are merged with other relevant variables, such as income and energy prices, to provide a measurable final energy consumption results [7,18]. This approach requires the availability of long historical datasets and is usually used in comparison studies for different countries (Swan and Ugursal, 2009). Other studies (Guan, 2009; Krese, Prek and Butala, 2012) have implemented a variant of CDD accounting for humidity, referred to wet-bulb CDD (CDD_{wb}). CDD_{wb} essentially replaces outdoor air temperature or the dry-bulb temperature (T_d), with outdoor air temperature accounting for Relative Humidity (rh) computed using wet-bulb temperature (T_{wb}) (Mistry, 2019).

However, other relevant factors, such as equipment efficiency, population size, AC appliance ownership, and building characteristics such as building materials, envelope and type, (IEA, 2018) also influence the energy demand for space cooling. A growing number of studies have been directed toward the use of CDD combined with other approaches to provide energy-related results (Isaac and van Vuuren, 2009; De Cian *et al.*, 2019; Randazzo, De Cian and Mistry, 2020). Bottom-up models, or buildings detailed simulation models, are largely used for single country analyses. These models require a significant amount of detailed data (Swan and Ugursal, 2009). This kind of approach is used to understand the role of building types on the demand for heating or cooling loads, or to understand the role of efficiency measures on total energy consumption, using the CDD as one modeling parameter (Daioglou, van Ruijven and van Vuuren, 2012; De Rosa *et al.*, 2014; Invidiata and Ghisi, 2016).

Regarding geographical coverage, most studies have investigated the effects of climate change on cooling energy consumption in developed countries (Li, Yang and Lam, 2012; Dirks *et al.*, 2015; Reyna and Chester, 2017; Kitous and Després, 2018; Andrić, Koc and Al-Ghamdi, 2019). However, there are fewer studies that investigate the impact of air temperature on indoor cooling services and energy demand in emerging economies [9,30], and specifically in Brazil [7,25]. Regional studies are relevant for this kind of analysis given their greater granularity with respect to local climate and socioeconomic circumstances, which can be used to further explore regional differences

(Kitous and Després, 2018). This is particularly the case of Brazil, where the country's five geographical regions present different social-economic and climate patterns [7,25].

Brazil is a relevant case study, being a tropical developing country with a warm climate and an income driven rise in ownership of AC equipment. The country's AC ownership rate in the residential sector increased by 9% per year between 2005 and 2017, and is expected to continue to grow (EPE [Empresa de Pesquisa Energética], 2018). However, existing studies about the impacts of climate change on space cooling in Brazil assess the effects of air temperature and humidity on energy demand without considering different patterns of consumption and regional effects [7,25,32], or possible technological changes [12, 33]. To date and to the authors' knowledge, no study has specifically analyzed Brazil with a focus on its regional particularities, less so by applying a hybrid methodology that integrates the use of CDDs and end-use modelling.

This paper assesses the impacts of climate change on thermal parameters, and how this would affect space cooling energy consumption in Brazilian households. Future climate projections from an ensemble of thirteen experiments of the HadGEM3-A 3.0 (Hewitt *et al.*, 2011) and EC-EARTH3.1 (John Donners, Chandan Basu, Alastair McKinstry, Muhammad Asif, Andrew Porter, Eric Maisonnave, Sophie Valcke, 2012) General Circulation Models (GCMs) under three Specific Warming Level (SWL) scenarios (1.5°C, 2°C and 4°C) are used to assess the effect of climate change, *ceteris paribus*, on a static energy system for Brazil. The methodological approach is divided into two parts for each SWL scenario: (i) climate data analysis and calculation of CDD_{wb}; and (ii) the application of an end-use model to estimate total electricity demand for space cooling. The role of improved energy efficiency is also assessed and discussed to understand the extent to which it could avoid positive feedbacks from AC as an adaptation measure.

The structure of the paper is organized as follows. Section 2 describes the research methodology Sections 3 and 4 present the study's results and discusses its main findings and limitations, suggesting improvements for future work. The conclusions of the study are found in Section 5.

4.3 Methodology

The methodological procedure used in this study is articulated into two parts, which are summarized in Figure 13 and detailed in the following subsections. The first part computes gridded/regional CDDs based on wet bulb temperature (T_{wb}), calculated using near-surface dry bulb temperature (T_d) and the relative humidity of the air (rh). By incorporating rh, CDD_{wb} accounts for a better thermodynamic limit on human metabolic heat transfer (Sherwood and Huber, 2010), particularly relevant for humid regions like Brazil [17, 21, 20]. Although CDD_{wb} do not contains information on human behavior nor on buildings' features for a precise estimation of cooling energy needs, it can provide a comparative measure of ambient thermal comfort (Petri and Caldeira, 2015), being a spatially explicit indicator of gross demand for space cooling.

We considered three scenarios of SWL describing different adaptation challenges and changes in future projected CDD_{wb} relative to the baseline scenario – it indicates the locations where space cooling needs are projected to increase (or decrease). Based on CDD_{wb} projections, we also compute dummy value matrices, here referred to as "on-off matrices", containing information about the number of days per year that cooling appliances need to be turned on in each municipality. The indication provided by the on-off matrices is used as an input for an end-use model to estimate the increase in space cooling electricity demand for the Brazilian residential sector, considering demography, appliance ownership, and efficiency rates.

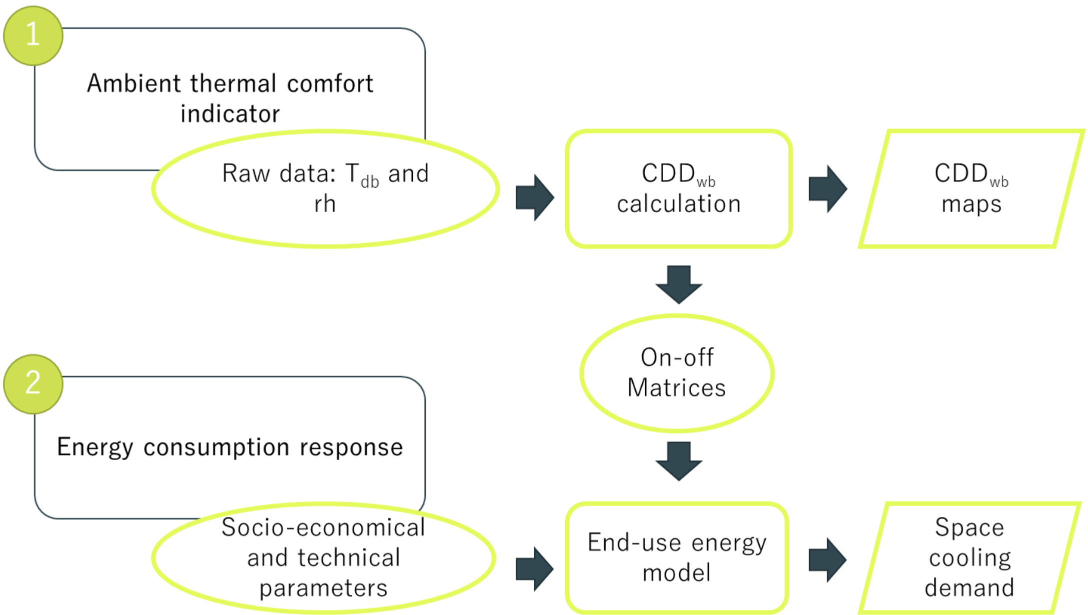


Figure 13. Flowchart of the study method

Note: T_d is the average daily near-surface dry bulb temperature (°C), and rh the average daily near-surface relative humidity (%). CDD_{wb} is measured in °C-days.

4.3.1 Ambient thermal comfort indicator

4.3.1.1 *Dataset description*

The study assessed a baseline scenario and three SWL scenarios assuming 1.5℃, 2℃ and 4℃ global average temperature increase when compared to pre-industrial levels. The data employed to calculate the CDD_{wb} derived from two sources. The first data source includes historically observed meteorological variables and was obtained from the Global Land Data Assimilation System (GLDAS) (Rodell *et al.*, 2004). The variables T_d in degree Celsius (°C) and rh in percentage (%) were assembled from GLDAS at a daily timescale for the 1970-2009 period. They were used to elaborate the baseline scenario and to correct biases in future climate projections. GLDAS has global time series at a high spatiotemporal resolution (0.25° gridded at 3-hourly time steps [17, 38]).

The second data source used refers to climate variables for each SWL scenario from the Helix project[16], which conducts simulations of present and future climate. The

[16] For more information, see https://helixclimate.eu/

project uses two GCMs and their respective experiments: HadGEM3-A 3.0 (six experiments with a resolution of ~ 60 km) and EC-EARTH3.1-A (seven experiments with a resolution of ~ 40 km). Each experiment results in a different evolution of the average surface temperature over time, so the SWL period is defined by the year when global average temperature reaches the respective warming level (1.5°C, 2°C or 4°C) plus and minus 15 years, resulting in a 30-year period for each scenario and each experiment. The variables retrieved from the Helix project database are maximum dry bulb air temperature (Td_{max}), minimum dry bulb air temperature (Td_{min}); and average rh, all at daily timescales. Data for the simulated historical period of 1981-2010 are also retrieved from this database for the bias correction procedure, which is further detailed in the following section.

4.3.1.2 *Climate data analysis and computation of CDD_{wb}*

Due to limitations in climate models, such as spatial resolution constrains, simplified physics and thermodynamic processes, data simulated by GCMs are often biased (Maraun, 2016). Thus, projected climate data were analyzed and treated to remove GCM biases before the CDD_{wb} calculation. The bias correction was based on the raw climatic data of T_d and rh from GLDAS (Mistry, 2019), using a methodology of nudging or simple bias correction. It calculates the variation between the observed historical[17] data and the simulated historical data, which is then added to the modeled projections of future SWL scenarios (Hawkins *et al.*, 2013). Specifically, for the rh data, as the values are limited between zero and 100%, a restriction is imposed to keep parameter values within this range after calibration. The grid conversions of GCMs (coarser resolution) to GLDAS (0.25°), and the subsequent data operations involved in bias corrections were performed using the Climate Data Operators (CDO) software (Schulzweida, 2019). The bias corrected T_d and rh were used to calculate the average T_{wb} for the baseline and for each GCM experiment for each SWL scenario using the Equation 10**,** following Stull (Stull, 2011):

$$T_{wb} = T_d * atan(0.152 * (rh + 8.314)^{0.5}) + atan(T_d + rh) - atan(rh - 1.676) + 0.00392 * rh^{1.5} * atan(0.023 * rh) - 4.686$$

Equation 10

[17] For more information, see Mistry (2019) (Mistry, 2019)

where T_{wb} is the wet bulb temperature (°C), T_d is the average daily dry bulb temperature (°C) calculated as an arithmetic average of the maximum and the minimum temperature (°C), and *rh* is the relative humidity in %. The *atan* symbol stands for the arctangent operator. A detailed explanation of the physical coefficients values in the equation is available in Stull [32].

Following the computation of T_{wb} on the 6 (7) individual ensemble members of HadGEM3-A 3.0 (EC-EARTH3.1-A), we extract the median T_{wb} across the combined 13 ensemble runs for each SWL. The subsequent single daily time series spanning 30 years for each SWL scenario was then used to compute the long-term daily averages, thus resulting in a single daily time series of a representative future year, for each SWL scenario. .

Thereafter, the calculation of CDD_{wb} for the baseline and each SWL scenario was performed. The methodology to compute the CDD_{wb} considers the daily average of the T_{wb} and a reference temperature (T_{base}). The CDD_{wb} calculation follows (Mistry, 2019) by using an adapted equation of the American Society of Heating, Refrigerating and Air Conditioning (Owen, 2009), presented in Equation 11 as:

$$CDD_{wb} = \sum_{i=1}^{n} (T_{wb} - T_{base})^{+}$$

Equation 11

where T_{base} is representative of a threshold value for the use of air conditioning in °C, and '+' indicates that only positive values are considered for summation over the time period n (typically months or year).

Different studies assume different values for T_{base}, typically ranging from 18°C to 25°C (Mistry, 2019). In this work, the reference temperature adopted, on a conservative basis, is 24°C. It must be noted though that like T_d, T_{wb} is also measured in °C. Typically for a given environmental condition, by definition, T_{wb} is lower than T_d. The accumulated monthly or annual CDD_{wb} therefore also register lower degree-days compared to CDD (based on T_d). The reference temperature chosen in this study can be therefore considered as being equivalent to a higher T_{base} if measured on a dry-bulb scale. For a detailed discussion, readers are guided to (Mistry, 2019).

CDD_{wb} maps were created for the baseline and SWL scenarios for visual analysis of the gross cooling needs over the Brazilian territory due to the different warming levels using the QGIS 3.4 software (QGIS Development Team, 2020). Therefore, we define in this work CDD_{wb} as an index for ambient thermal comfort needs of a region.

Matrices with dummy values are generated for each scenario, in which "one" is attributed to the days when T_{wb} is greater than T_{base} and "zero" otherwise. These matrices contain information about the days in the representative year of each scenario when a cooling device in a given location is used to reach a given indoor temperature. In other words, it provides information on the days of use of AC appliances, which are an input for the end-use energy demand model. Hereafter, these matrices are denominated "on-off matrices".

4.3.2 Energy consumption response

4.3.2.1 *Space cooling energy demand*

An end-use model is developed and applied to assess the energy consumption response to changes in temperature and relative humidity. The model considers demographic and socioeconomic characteristics and uses outputs from the CDD_{wb} calculation, through "on-off matrices", to project air conditioning electricity consumption for Brazilian households.

Demographic characteristics are important when assessing the impact of climatic variables on energy consumption, especially because of the particularities of Brazil. The country has an extensive area with an unequal population density (IBGE, 2017a, 2020b). While the country has an average population density of 22.4 people per square kilometer, the country's Southeast region has an average density of 139.3 against 4.1 people per square kilometer in North region (Table 8). Therefore, ambient thermal comfort needs, indicated by CDD_{wb}, in a location may not be translate into relevant energy consumption if local population is small.

Table 8: Population per square kilometer in Brazil

Region	Population	Total area (km^2)	Population density
North	15,864,454	3,851,281	4.1
Northeast	53,041,263	1,551,991	34.2
South	27,386,891	924,565	29.6
Southeast	80,364,410	576,743	139.3
Midwest	14,058,094	1,606,239	8.8
Brazil	**190,715,112**	**8,510,821**	**22.4**

Source: (IBGE, 2017a, 2020b)

The same geographical differences are observed when considered socioeconomic characteristics (IBGE, 2017b, 2019b). In this paper this heterogeneity is reflected by the differences observed in ownership rate of an AC unit across regions, that is dependent of cultural and economic household characteristics, besides climate parameters (Depaula and Mendelsohn, 2010).

End-use energy models can be applied at different geographical levels, depending mostly, on the data availability (Swan and Ugursal, 2009). In our study, gridded weather data are available at a high granularity. Despite this, technical parameters for the AC units are only available for Brazilian macro-regions.

As the energy model used here relies on parameters at the regional level, the average daily dry bulb temperature (T_d) and on-off matrices were first converted from grids to the Brazilian municipalities' polygons[18]. Next, T_d data for each of the 5,569[19] Brazilian municipalities were crossed with on-off matrices data, that indicates the days when an AC unit is in use for ambient cooling. Municipalities data were then aggregate to the macro regional[20] level using a temperature-population weighted methodology for days of use. Using this approach, the ambient temperature (T_{amb}) for each Brazilian macro region was calculated for the end-use model.

[18] A zonal statistics-based script was developed in the R software [46] for that purpose, using the median values of the pixels inside the municipal polygons.

[19] Brazil as of present has 5,572 municipalities (IBGE, 2017a), but three of them (Raposa, Lucena and Fernando de Noronha) were not independent municipalities during the database's timeframe.

[20] Brazil officially divided into 5 macro geographical regions: North, Northeast, South, Southeast and Midwest. This macro region definition is been used since 1970 (IBGE, 2017a).

Subsequently, the thermal load of AC appliances was calculated. The thermal load, or cooling load, is proportional to the heat transfer needed to achieve an indoor set temperature. The higher the outdoor temperature, the more energy air conditioning consumes to guarantee the same indoor temperature set by the user (Nogueira, 2013). A set of 20 thermal loads for representative AC devices were calculated according to four scenarios (baseline plus SWLs) and five geographical regions in Brazil. The calculation was inspired by (Cardoso *et al.*, 2012) and follows Equation 12 and Equation 13 bellow:

$$Q_{i,j} = Q_s * L_{i,j} * h$$

Equation 12

in which:

$$L_{i,j} = \sum_{d=1}^{365} l_{i,j} = \sum_{d=1}^{365} \frac{(T_{amb,i,j} - T_{int})}{(T_{amb,s} - T_{int,s})}$$

Equation 13

where, Q is the thermal load in kWh; i is the scenario (baseline and SWL); j is the geographical region in Brazil; Q_s is the nominal thermal load of an appliance in standard conditions in kWh; L is the annual thermal load correction[21]; h is the hours of use; l is the daily thermal load correction factor; T_{amb} is the average external/outdoor temperature in °C; T_{int} is the average indoor temperature of use (set as 24°C); $T_{amb,s}$ is the external temperature on standard test conditions (set as 35 °C); and T_{int} is the indoor temperature of use on standard performance test conditions (set as 26.7 °C)[22] (Cardoso *et al.*, 2012).

[21] The correction factor considers air-conditioner operation at different external temperatures in comparison to the reference external temperature of 35°C, applied in air-conditioners performance tests.

[22] Air conditioning performance depends on dry temperature effects difference, the effects of humidity are not important for the appliance operation.

The thermal load correction factor (l), is calculated for those days in each scenario when an AC appliance is used to reach a set indoor temperature, given by the on-off matrices. Temperatures difference effects on the annual load (L) depends on the annual days of use and the outside temperature (T_{amb}).

The effects of different external temperatures are isolated using one representative standard AC device[23] for each of the 20 cases. In each case, the increase in the thermal load of the representative AC is a result of different estimated ambient temperature scenarios. The same logic is assumed for by the Unit Energy Consumption (UEC), Equation 14. Considering the same Coefficient of Performance (COP) – standardized technical parameter –, the increase in thermal load is equal to the increase in energy needs [33, 44]:

$$UEC_{i,j} = \frac{Q_{i,j}}{COP}$$

Equation 14

Finally, the total air conditioning electricity consumption for the different temperature scenarios and geographical Brazilian regions was calculated following Equation 15 (Barnett and O'Neill, 2010; Depaula and Mendelsohn, 2010):

$$EC_{air\ conditioning,i,j} = UEC_{i,j} * \ pop_j * \ ownership\ rate_j$$

Equation 15

where, $EC_{air\ conditioning}$ is the air conditioning electricity consumption; i is the scenario (baseline and SWL); j is the regions; pop is the population; and $ownership\ rate$ is the percentage of households with AC equipment.

The parameters used in Equation 15 are presented in Error! Reference source not found.. The daily hours of use were based on (EPE [Empresa de Pesquisa Energética], 2018). Capacity of the representative AC unit was set as 2.6 kW and COP set as 3.02 W/W (González-mahecha *et al.*, 2019). Ownership rates for each region were taken from

[23] Same standard technical parameters, same internal temperature set and same threshold temperature of decision to use.

(IBGE, 2017b). These values represent the average parameters for a representative AC unit in Brazil in 2000-2010, period of our historical temperature data.

Recent studies show that the power capacity of an average AC unit for Brazil increased in the last years [31, 49], especially considering the penetration of split AC technology replacing window ACs [47]. Also, in 2020, there was an update in the Brazilian labeling program for AC units. The new metric considers a seasonal efficiency index, replacing the earlier COP metric (Ministério da Economia/Instituto Nacional de Metrologia, 2020), and was adopted to account for the increased penetration of the inverter AC technology (Gomes, Costa and Jannuzzi, 2018; Park *et al.*, 2019). The inverter technology improves the efficiency of an AC unit since it can work on full or partial loads, and this can only be accessed with the use of a seasonal metric (IEA, 2018). The Cooling Seasonal Performance Factor (CSPF), now adopted in Brazil as a new energy efficiency' label, will be able to better reflect the new AC appliance fleet[24].

As our methodology to define energy demand considers power consumption variation according to external temperature variations, it can be considered aligned with CSPF methodology. For that, we chose to keep COP as a single historical metric and do not change to the new CSPF standard. This approach helps us to isolate the impact of temperature increase in the energy consumption, when comparing climate parameters observed historically with future scenarios. So, the chosen AC unit did not suffer variations during the scenarios and remained the same as in the average for the historical period considered.

Finally, the associated GHG emissions from the projected additional electricity consumption were calculated for each SWL scenario applying three different annual electricity grid emission factors for Brazil. GHG emissions due to electricity consumption depends on the fuel mix used for electricity generation. In the case of Brazil, the grid emission factor varies annually, largely due to the variability of hydropower (Ministério da Ciência Tecnologia Inovações e Comunicações - MCTI, 2020). Therefore, we tested the impact of three different grid emission factors, assuming the average, lowest and the highest historical emission factor in the period ranging from 2015 to 2019 (respectively

[24] Air conditioner producers and retailers have until 2025 to adapt to the new metric (Ministério da Economia/Instituto Nacional de Metrologia, 2020).

0.0896 tCO_2/MWh , 0.0246 tCO_2/MWh and 0.1355 tCO_2/MWh (Ministério da Ciência Tecnologia Inovações e Comunicações - MCTI, 2020)).

4.3.2.2 *Sensitivity analysis*

Energy efficiency is considered an important measure to reduce space cooling energy demand (Alves, Duarte and Gonçalves, 2016; Gomes, Costa and Jannuzzi, 2018). The use of efficient appliances could help avoid the feedback loop associated with global warming scenarios (IEA, 2018).Therefore, for a given thermal load requirement, higher AC COP values have the potential to reduce air conditioning energy demand. A sensitivity analysis for the energy efficiency of AC appliances was thus deemed necessary and conducted as explained below.

According to the Brazilian labeling program (INMETRO, 2017), appliances can be identified according to their efficiency level. The most efficient appliances available in the market are classified as label "A", while label "D" is granted to the lowest efficiency devices. The COP values for ACs available in the market in 2017 vary between a minimum requirement of 2.30 W/W (label D) and 3.23 W/W (label A) (INMETRO, 2017). Such a range is close to the COP mean value found for international markets, 3.0 W/W (IEA, 2018). However, when compared to the best available technologies worldwide, these technologies are still lagging. The best AC international devices present COP values above 6.0 W/W, almost twice the value found in the Brazilian market. The new labels defined in Brazil in 2020 come closer to the best available technology observed internationally. For 2025, an inverter AC with label "A", considering a seasonal metric (CSPF), will have a minimum efficient requirement of 7.00 W/W. However, window AC appliances should not have a significant increase in its standard (Ministério da Economia/Instituto Nacional de Metrologia, 2020). Considering this new seasonal metric, AC sales in Brazil would be better aligned to the best technology available in the world (IEA, 2018). Nevertheless, the average efficiency of existing appliances will also depend on the existing stock and its lifespan (National Association of Home Builders and Equity, 2007; Cardoso *et al.*, 2012).Taking this into consideration, efficiency improvement scenarios (IEA, 2018; Colin Taylor, Eric Gibbs, Ana Maria Carreño, Suely Carvalho, 2019) and a market survey led by the Brazilian Energy Research Company (EPE [Empresa de Pesquisa Energética], 2018) were analyzed to set a value for the sensitivity analysis. A COP value of 4.79 W/W was assumed, an almost 60% increase, in line with the best AC available in Brazil (INMETRO, 2017). It is important to highlight, that in the last 12 years there has been only an increase of 8% in average AC efficiency levels in Brazil (EPE [Empresa de Pesquisa Energética], 2018).

We also tested the sensitivity of result to different ownership rates. In Brazil there was a significant increase in AC ownership rate between 2005-2017, of 9% per year (EPE [Empresa de Pesquisa Energética], 2018). This was mostly due better affluence conditions observed in the country (EPE [Empresa de Pesquisa Energética], 2018)(González-mahecha *et al.*, 2019)(Sanches-pereira, Gustavo and Teixeira, 2016). Looking into the future, higher temperatures will be an additional factor increasing AC ownership rates even more (Depaula and Mendelsohn, 2010). To capture the temperature and economic-related heterogeneity of ownership rates, the highest AC ownership rate among the States in a specific region was selected as benchmark for that region[25] (Table 9).

Table 9: Technical and socio-economic parameters for electricity air conditioning household consumption for base case and sensitivity

	Base case			Sensitivity		
Region	Ownership rate (%)	COP (W/W)	Q (kW)	Ownership rate (%)	States considered	COP (W/W)
North	14.8	3.02	2.6	29.2	Amazonas	4.75
Northeast	5.1			10.0	Piauí	
South	8.2			19.1	Santa Catarina	
Southeast	13.0			26.6	Rio de Janeiro	
Midwest	7.5			12.9	Mato Grosso do Sul	

Source: (IBGE, 2017b; EPE [Empresa de Pesquisa Energética], 2018; González-mahecha *et al.*, 2019)

For both sensitivity analyses, the emissions associated with energy consumption were calculated. Once again, three different emissions grid values were chosen to account for the uncertainty of these parameter.

[25] The Federation Units are a more aggregate geographical level when compared to the municipalities, but unfortunately, ownership data for municipalities were not available.

Results

4.4.1 Ambient thermal comfort and energy consumption response

4.4 Figure 14 shows the distribution of $CDDs_{wb}$ over the Brazilian territory for the historically observed data and the SWL scenarios. Municipalities with population higher than half a million people in 2010 are highlighted in circles. Results show that the highest growth in CDD_{wb} occurs in locations with low population density. For instance, the two largest cities of Brazil – São Paulo and Rio de Janeiro, both in the Southeast region – are relatively less impacted in the SWL scenarios than municipalities in the North region, which have a much smaller population density (Table 8). The exception to that trend is the city of Manaus, which is in the center of the Amazon rainforest, in the North region of the country, and has the seventh largest population of Brazil (IBGE, 2020b).

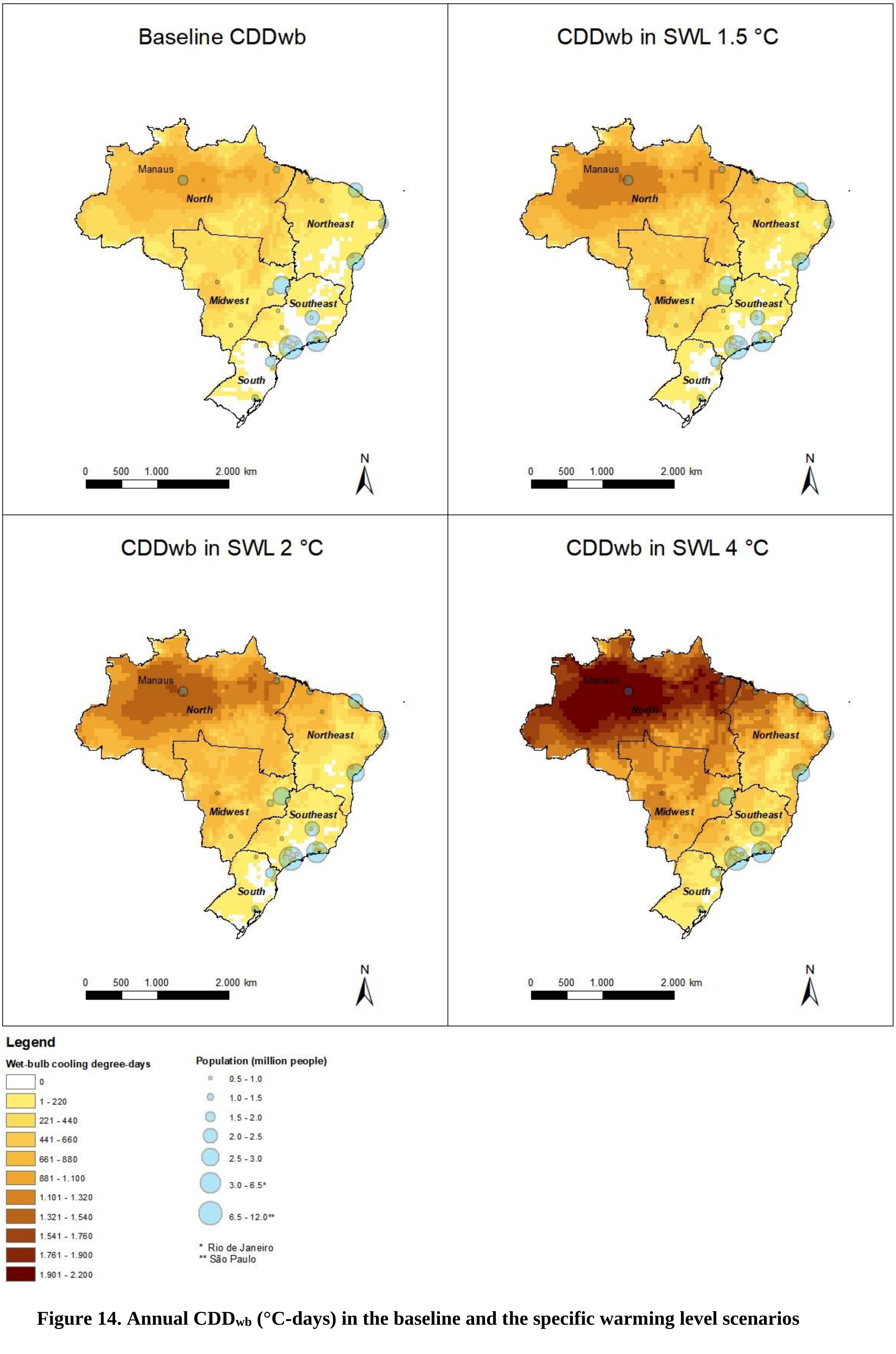


Figure 14. Annual CDD_{wb} (°C-days) in the baseline and the specific warming level scenarios

Figure 15 shows the monthly distributional effect of temperature in household energy use for Brazilian geographical regions. It shows the number of days per month that space cooling is needed in a region to reach the threshold ambient thermal comfort temperature, given by the average of all municipalities contained in that region. This result comes from the municipalization of the on-off matrices data.

The different Brazilian regions maintain their seasonal behavior for AC use in the projecting SWL scenarios. The curve shows a valley during cold months, especially in winter (June to August). It should be noted, however, that space cooling is needed even during the winter in the Brazilian North and Northeast regions. It is also important to note that, in the SWL 4^{o}C scenario, South, Southeast and Midwest space cooling off-season lasts two months less when compared to the baseline and the other SWL scenarios.

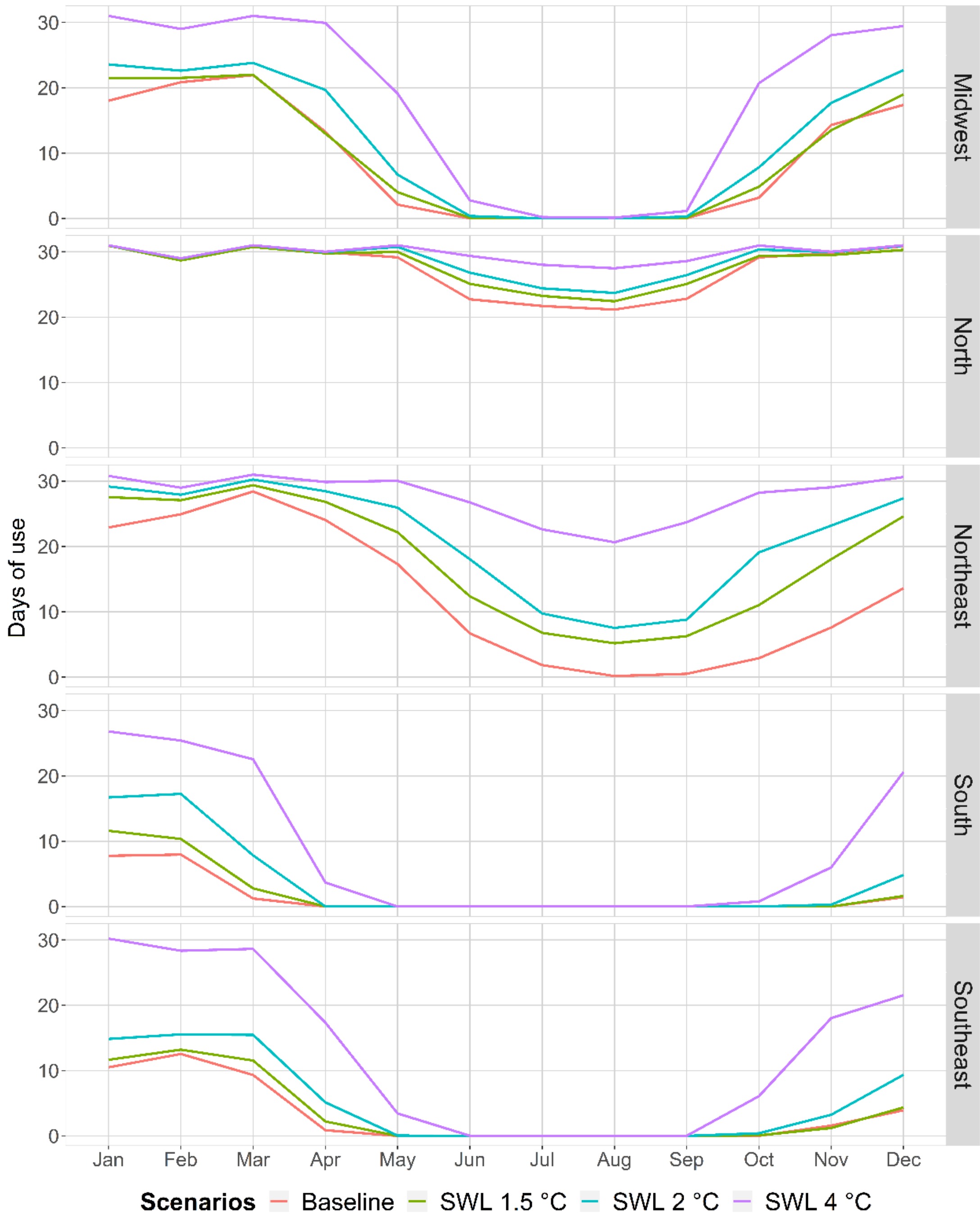


Figure 15. Space cooling days of use per month in Brazilian regions from on-off matrices

According to the results presented in Table 10, the North region shows the lowest percentage increase in days of use in all the SWL scenarios. This is because the region already has an average of 328 days of use in the baseline scenario. So, the number of days that needs space cooling services in the region has already saturated. Despite this, the North has a relevant increase in thermal load in SWL scenarios due to the increase in ambient temperature, as shown in Figure 14.

Table 10: Ambient thermal comfort response assuming a representative AC device compared with the Baseline scenario

Region	SWL 1.5°C scenario		SWL 2°C scenario		SWL 4°C scenario	
	∆ annual days of use	∆ thermal load factor	∆ annual days of use	∆ thermal load factor	∆ annual days of use	∆ thermal load factor
North	2%	53%	5%	78%	9%	155%
Northeast	44%	30%	70%	44%	120%	85%
South	44%	119%	161%	180%	489%	431%
Southeast	13%	152%	64%	194%	295%	325%
Midwest	7%	104%	31%	166%	100%	346%
Brazil	**25%**	**63%**	**50%**	**89%**	**127%**	**169%**

Note: Brazil values was calculated as a weighted-population average.

The most significant impacts in relative terms are observed in the South and Southeast regions. In the South region, less than 50 days of use are estimated for most municipalities in the baseline scenario. This is explained by the fact that the South is the Brazilian's coldest region. However, in the SWL scenarios some municipalities surpass 100 days of use. Also, on average, the impact of temperature on energy consumption response in the South region is estimated to an almost 5-fold increase. As for the Southeast region, the highest impact comes from the thermal load effect in lower temperature SWL scenarios, with the effect of days of use becoming more relevant at warmer SWLs.

For Brazil, as seen in Table 10, the average AC equipment days of use increases more than 100% in SWL 4^{o}C. This would substantially impact the need for space cooling and consequently the associated energy consumption. Nevertheless, it is important to notice that the individual behavioral conditions, and cultural aspects not considered, could influence the decision to use an AC. Results above are only an indication of thermal comfort through a CDD_{wb} analysis.

Figure 16 shows results for the ambient thermal comfort evaluation, indicated by average CDD_{wb}, and the respective energy demand response. The North is the region with the highest average CDD_{wb} in all scenarios. However, due to its low population density

(Table 8), the potential impact on energy demand is not large. Nevertheless, the region's share in total AC energy consumption of Brazil is still meaningful because of the high average ownership rate in its major cities.

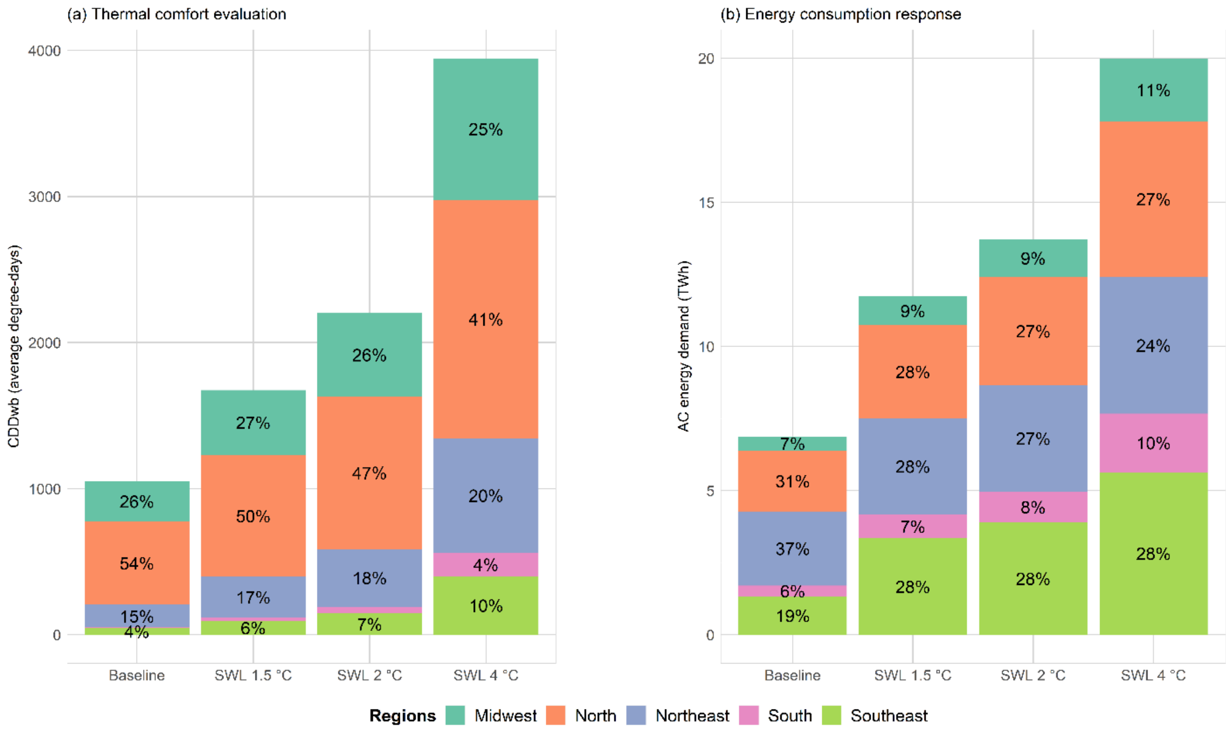


Figure 16. Ambient thermal comfort evaluation versus (a) energy consumption response (b) by SWL scenarios and regions

On the other hand, as the SWL rises, the share of the Southeast in total AC demand also increases, becoming the most relevant. However, its absolute growth in average CDD_{wb} is quite modest in comparison to the North, Northeast and Midwest regions. This can be explained by the high population density of the Southeast region (Table 8), as well as its high average ownership rate (Table 9).

The results for the South region are a particular case. The increase in average CDD_{wb} and the AC energy demand are low compared to other regions in absolute terms. However, the region shows a large relative growth in both parameters for higher SWL. This growing thermal discomfort in a region not used to warmer conditions can induce significant local impacts, especially regarding behavioral aspects.

Comparing the trends of increase in the average CDD_{wb} and the AC energy consumption at the national level (Figure 16), both curves show similar behaviors. Notwithstanding, a local level assessment of thermal comfort evaluation and response shows different increase trajectories for the parameters.

Figure 17 shows CO_2 emissions associated with AC electricity consumption in Brazil for the proposed scenarios, assuming current values for energy efficiency and historical grid emission factors. Considering the historical average for the grid factor, CO_2 emissions in the baseline are 0.62 Mt of CO_2 and increase by 70%, 99% and 190% in the SWL 1.5 °C, SWL 2 °C and SWL 4 °C scenarios, respectively. The effects of a variation in these parameters and their impact on CO_2 emissions can be very significative and is assessed also in Figure 17.

It is important to notice the role of the grid emission factor. Assuming Brazilian lowest historical value of grid emission factor, representing a decarbonization of electricity generation scenario, an increase in energy consumption would not necessarily increase CO_2 emissions.

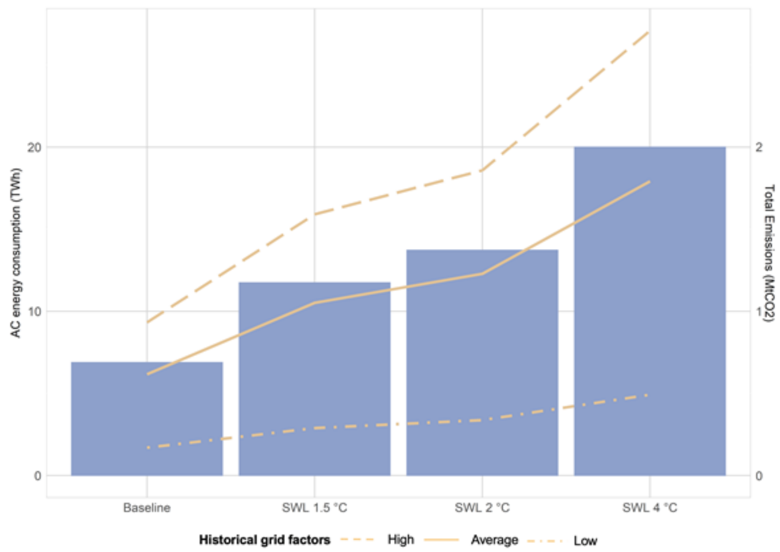


Figure 17. Electricity consumption and associated CO2 emissions by scenario

4.4.2 Sensitivity analysis

Figure 18 shows the results of a sensitivity analysis for the energy efficiency in the AC energy consumption. Considering an energy efficiency improvement of 59% in AC appliances, or a 4.79 W/W COP, the energy consumption response drops by 37% in the SWL scenarios. In absolute terms, this represents a saving of 4.3 TWh per year in the in the SWL 1.5°C scenario and of 7.4 TWh in the SWL 4°C scenario. The contribution of efficiency measures becomes even more important when considering the evolution on ownership rates of AC appliances in Brazil. Accounting for the potential increase in AC ownership increases Brazilian energy consumption by about 125%. Efficiency devices in this case could avoid 16.6 TWh energy consumption yearly on the highest temperature scenario.

As a sensitivity test for the COP values, we evaluated the efficiency improvement needed to keep the same level of energy consumption as in the baseline temperature scenario and compare it to the current best available technology observed in Brazil. In order maintain baseline energy consumption, AC efficiency would need to improve to a COP value of 5.15, 6.02, and 8.77 for the SWLs 1.5 ^{o}C, 2 ^{o}C and 4 ^{o}C scenarios, respectively. The average efficiency levels to compensate the effects of a temperature increase in energy consumption in SWL 1.5 ^{o}C and SWL 2 ^{o}C scenarios are below the new standards of the Brazilian labeling program (Ministério da Economia/Instituto Nacional de Metrologia, 2020). However, for SWL 4 ^{o}C the challenge will be bigger, requiring average COP levels of the best available technology observed internationally in 2018 (IEA, 2018).

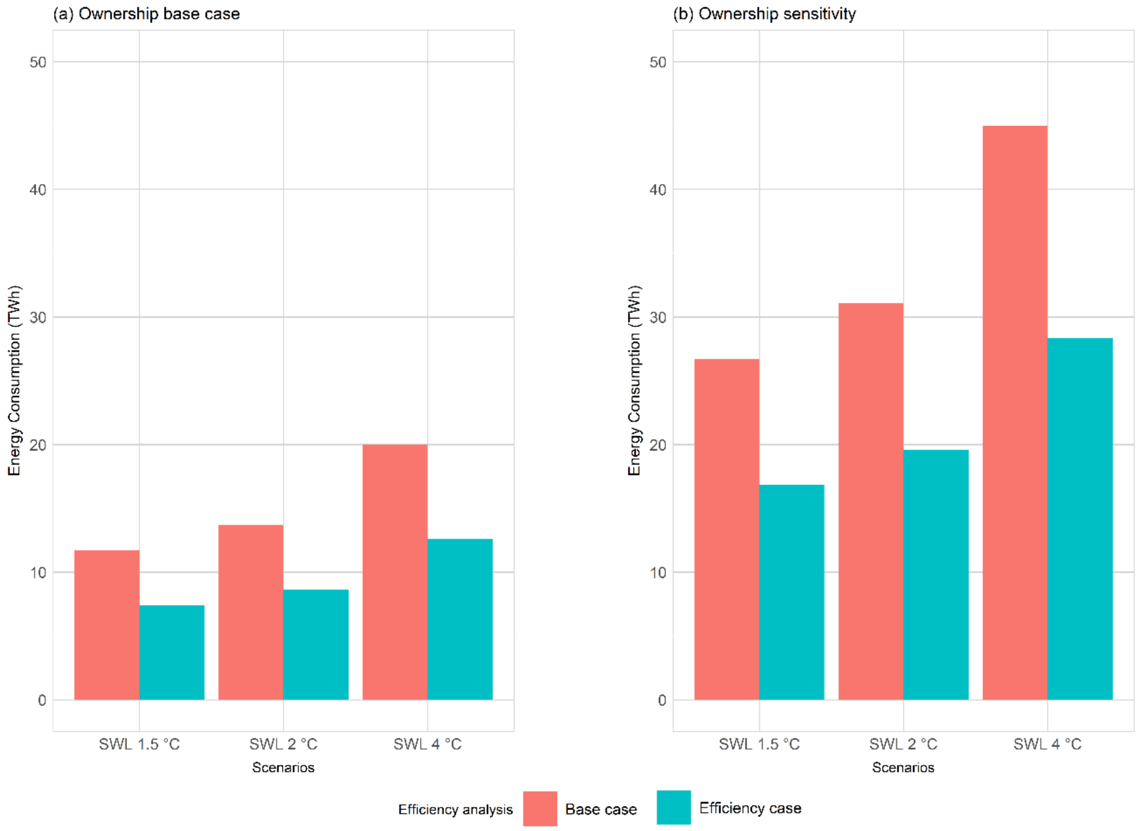
CO_2 emission levels decrease significantly with higher efficiency AC equipment. Table 11 shows that the use of a better appliances could avoid more than 1.0 Mt of CO_2 yearly in the ownership base case scenario and could achieve a save of 2.3 Mt under higher rates of AC appliance ownership[26].

Table 11: Avoided emissions with the use of efficient AC appliances in different ownership sensitivity cases

	Ownership base case			Ownership sensitivity case		
Avoided emissions (Mt of CO2 / year)	High	Averag e	Low	High	Averag e	Low
SWL 1.5°C	0.6	0.4	0.1	1.3	0.9	0.2
SWL 2°C	0.7	0.5	0.1	1.6	1.0	0.3
SWL 4°C	1.0	0.7	0.2	2.3	1.5	0.4

[26] The highest historical emission grid factor is assumed.

Both the energy consumption and the CO_2 emissions present a considerably smaller relative growth for warmer climate conditions in the high efficiency scenario, meaning that policies fostering energy efficiency can attenuate part of the impacts of higher temperatures on energy demand and associated CO_2 emissions for additional space cooling needs.



4.5 **Figure 18. Energy consumption response with efficient AC appliances and standard AC appliances by different ownership scenarios**

Discussions and limitations

Space cooling currently represents a significant share of residential electricity demand in Brazil (about 14%) and is expected to increase with climate-induced temperature growth (EPE [Empresa de Pesquisa Energética], 2018). A strong relationship between climate change and higher energy demand for thermal comfort has been reported in the literature (Davis and Gertler, 2015; Dirks *et al.*, 2015; Clarke *et al.*, 2018). However, no data was found on the association between CDD_{wb} methodology to end-use energy demand models, providing a comprehensive assessment of energy demand impacts, considering climate, demographic, technical and socioeconomic variables The methodology used could be easily adapted to different regions or countries and combines an easy approach to evaluate behavioral aspects of consumption combined with climate change scenarios.

This study assessed the energy implications of an increased number of days with high thermal load requirements for operating AC equipment by using CDD_{wb} projections as input in an end-use energy model, which brings two main advantages. Firstly, the georeferenced grid of the on-off matrices makes it possible to evaluate regions at different scales according to the necessary input used in an end-use model. Secondly, the methodology also considers a metric appropriated to humid countries and regions, like in Brazil, by including relative humidity for temperature set point.

Results show an overall annual average increase in CDD_{wb} and energy demand across all SWL scenario. The seasonal pattern of space cooling, however, is not expected change significantly, if not in terms of duration, with the high-use season lasting for a longer period of time in some regions.

In addition to temperature, we highlight the importance of other geographical and socio-economic drivers', namely population and income. Although CDD_{wb} can be a good approximation of the ambient thermal comfort, actual aggregate energy consumption also depends on population density. These socio-economic drivers', such as population and income, are also important to assess for the trends in ownership rates and in the types of AC units used. In Brazil, there is a deficit in achieving ambient thermal comfort in many households, mostly due to budget constraints (Mastrucci *et al.*, 2019a). Consequently, rising income alone could intensify the total energy demand for space cooling in the country. This has been, to some extent, observed in the first decade of this century(González-mahecha *et al.*, 2019)(Sanches-pereira, Gustavo and Teixeira, 2016). Considering population and income increase alone, the ownership rate of space cooling appliances in Brazil can reach 96 AC units per 100 household in 2035, compared to a current average of 40 units (EPE [Empresa de Pesquisa Energética], 2018). The same trend of growth is observed for the power capacity of the appliances and the performance.

The outcomes of these socio-economical drivers, associated with increasing temperatures, could lead to higher energy consumption impact than those shown in this work, as shown by our sensitivity analysis. As also shown in the sensitivity analysis, efficiency improvements AC appliances can play an important role in attenuating the increase in energy use associated with rising temperatures. A comparison between the typically available AC technology in Brazil and the international efficiency standard indicates that the country is still far behind from the best efficiency level observed (IEA, 2018)(Ministério da Ciência Tecnologia Inovações e Comunicações - MCTI and ONU Meio Ambiente, 2017). The lack of updated data for technical parameters in Brazil to estimate energy demand in detailed end-use models is a limitation for studying Brazil. Many assumptions were made in this paper to go around this. Certainly, this can be improved in future studies as more information becomes available.

Energy efficiency policy in the buildings sector in Brazil is highly based on labeling programs (Ministério da Ciência Tecnologia Inovações e Comunicações - MCTI and ONU Meio Ambiente, 2017), which are less ambitious than those observed in other countries (Sanches-pereira, Gustavo and Teixeira, 2016). If higher efficiency levels are to be achieved, more ambitious energy efficiency policies will be needed. The trade-off between climate change mitigation and adaptation – higher energy demand for space cooling and respective GHG emissions – could be reduced by a continued decarbonization of the grid through higher use of renewables. Nevertheless, renewable energy is generally more vulnerable to climate change impacts [56]. This is specially the case of Brazil, where hydropower is the major source of electricity generation and could be severely impacted [57–59]. Higher energy demand and climate impacts on hydropower could have systemic repercussions across the power sector, with higher loads and higher use of fossil fuel power generation [26, 60]. Conducting integrated power system analyses considering multiple impacts on the power sector is recommended for future work. The methodology proposed here can be easily adapted to be included in energy systems models, integrating the demand results with supply-side climate impacts.

Moreover, the use of a unique temperature set point, despite the differences in terms of thermal acceptance and the wide range of climatic conditions between the country's regions, is a limitation of this study. Previous work show that there is a significant variation in acceptable indoor temperature in Brazil, ranging from 14°C to 32°C, depending on the location and methodology used (Lamberts *et al.*, 2013). Since this paper analyzes all Brazilian regions, a base temperature set at 24°C can be considered a suitable fitting. To some extent, the use of T_{wb} based on each region's relative humidity attenuates this simplification.

Finally, there is a lack of updated data for Brazil's technical parameters to estimate detailed energy demand for different municipalities, an improvement is recommended in future studies as more information becomes available. The methodology proposed here can be easily adapted to be included in energy systems models at any level, integrating the results of demand with other climate impacts and other sectors.

4.6 Conclusions

This study showed how Brazilian households can be affected by different climate change scenarios through variations in ambient air temperature and relative humidity and assessed its respective energy implications by merging the analyses of CDD_{wb} with an end-use model for electricity demand. The isolate effect of climate change scenarios in the use of AC units was estimated and showed a significative increase between 70% and 190%, depending on the scenario.

A high-resolution analysis of the CDD_{wb} indicator gives different measures of ambient thermal comfort accounting for both temperature and relative humidity, which are useful for large countries such as Brazil, which spans different latitudes and varying topography. Spatiotemporal heterogeneity in CDD_{wb} across Brazil provides a comprehensive visual indication of the distribution of impacts on the ambient thermal comfort in different warming scenarios. Moreover, this study showed that on-off matrices, a by-product of the CDD_{wb} calculation, can be useful inputs for end-use energy models as a regionally distributed proxy for the time-of-use variable.

Given Brazil's geographical and social heterogeneity, ambient thermal discomfort and energy consumption response are not linked across all regions. The study shows the relevance of identifying these singularities, showing a significant difference between increases in regional energy consumption. Thermal impacts on regions not densely populated, as the North region that has the highest value of CDD_{wb} across all SWL scenarios, showed less relevant impacts on energy use. Also, current regional disparities in AC equipment ownership, in absolute terms, indicate that the Southeast and South regions are expected to have larger increases in energy demand for space cooling. However, this effect could be widespread across the country as AC equipment ownership increases in all regions to justly provide thermal comfort to a larger share of the population. Higher space cooling equipment ownership may, indeed, be stimulated by warmer temperatures (De Cian *et al.*, 2019), leading to even broader energy demand impacts than those projected in this study (McNeil and Letschert, 2008).

The paper isolates the temperature effects on space cooling, but the effects of ownership increase are only demonstrated through a sensitivity analysis. Combining temperature and more AC appliances in Brazil can significantly increase energy demand, with a potential rise of 125%. It is important to highlight that temperature changes may also affect AC user behavior, a topic left for research in the future. Results from the sensitivity analysis indicate that energy efficiency can reduce the growth in energy consumption observed in warming scenarios. This suggests that the promotion of energy efficiency can be a suitable mitigation measure for the energy sector, reducing trade-offs with climate change adaptation measures. Expanding these results to a global scale, where space cooling needs are significant (Clarke *et al.*, 2018), efficiency could play a key role. The potential carbon emissions avoided by energy savings from efficiency measures depends on the fuel mix of the power sector. In Brazil, a 59% improvement of efficiency is feasible, compared to other countries, but would require more aggressive energy efficiency policies than those currently in place in the country (EPE [Empresa de Pesquisa Energética], 2018).

The results presented in this paper can therefore guide decision-makers to implement better mitigation and adaptation measures regarding thermal comfort and energy consumption response at the national and regional levels.

5 CONCLUSION

The present study explores the correlation between poverty, energy, and household's climate vulnerabilities in Brazil. Discussion on the access to reliable and affordable modern energy sources is one of the topics analyzed, for which few studies specifically cover the situation in Brazil.

To fill these research gaps, the three studies presented in this thesis have investigated the critical aspects of household energy use and associated welfare. By making (1) historical analysis of the rural electrification benefits, (2) assessing the evolution of energy poverty, and (3) evaluating the impacts of climate change on household energy use, this work contributed to the understanding of the context of energy poverty in Brazil and the extent of people's vulnerability to the consequences of climate change. The methodologies employed include econometrics, multidimensional energy poverty index, and a bottom-up energy use model to address the energy use in Brazil under different perspectives.

In the first paper (chapter 2), the results of the electrification program *Luz para Todos* was evaluated by correlating its impact to HDI at the municipal level. Findings show that the presence of electricity can be related to social development and that the education component of HDI was the most influenced by electrification. This study provided valuable insights to understand the limits of electrification gains and address complementary actions to benefit households from electricity access fully.

Considering the success of LpT program and the almost universal electricity access, the second work (chapter 3) intends to understand how energy poverty goes beyond physical access to modern energy sources. Considering the success of LpT and the reduction in the use of biomass for cooking, energy poverty is redefined, and its evolution in Brazil is assessed. Results show that physical access is no longer a major concern since some people are still not able to enjoy the benefits granted by electricity access fully. According to the results, 11% of Brazilian households are still energy poor. The outcome indicates that energy poverty is dependent on the context, varying upon time and changing according to region. Therefore, to eradicate energy poverty, it is needed to go beyond and understand its risks. Measures that could mitigate the vulnerability to energy-poor conditions should be mapped in advance.

The conclusion of the second study brings the discussion of the third study (chapter 4), which shows how Brazilian households can be affected by increasingly warmer temperatures caused by climate change. Findings suggest that energy use may increase between 70% and 190%, depending on the climate change scenario, due to the higher use of AC appliances. The use of more efficient appliances could partially compensate for the effects of climate.

In line with previous studies (Cook, 2011; World Bank and (ESMAP), 2015), this work demonstrates that electricity is key to improving living conditions, but there is a broader context that needs to be considered when it comes to eradicating energy poverty in all its dimensions (Middlemiss *et al.*, 2019). The findings from chapter 3 for energy poverty corroborate the insights of chapter 2. Between 2002 and 2017, it was possible to observe that the increase in electrification allowed families to increase the ownership of basic appliances, such as tv and refrigerator, improving communities' quality of life (IPEA and WWP, 2014).

The study presented in chapter 2 assumes a correlation between the social development index HDI and electricity access. Energy consumption can be associated with other social-development indexes, such as the Gini index, to understand the benefits of access to modern fuels (Pereira *et al.*, 2011; Sedai *et al.*, 2021). Energy poverty eradication has also been related to improving the population's living conditions (Oum, 2019). The use of energy in different forms can be linked to improving the way we live (Guzowski, Martin and Zabaloy, 2021). For that reason, it is possible to assume that to assure a decent living for the population; some efforts should be made to eradicate energy poverty in all its forms. More than that, by combining results observed in chapter 2 with the literature, we can assume that social development could be achieved when overcoming the energy poverty in Brazil. Also, the results in chapter 3 show that two dimensions of energy poverty were improved on the period observed. Correlating this result with those from chapter 2, we can infer that HDI indexes improvement can also have hidden results related to Ownership dimension evolution.

Energy access and ownership are only one part of the problem related to energy deprivation. The affordability issue is a persistent problem in Brazil, leaving people vulnerable in terms of energy use. The results in chapter 3 about clarify that energy poverty in Brazil is now highly associated with the Affordability dimension and is also associated with the income level, household conditions and surrounding infrastructure. The program Lpt was successful in understanding electricity as a way to improve the social conditions. Still, it was limited about the overall energy situation that those families have, especially regarding energy costs and access to efficient appliances. Also, the program was designed for rural areas, and nowadays, as shown in chapter 3, energy poverty goes beyond those areas, being an urban issue too. A new phase of social programs like LpT is now required to understand and assist energy use on all its aspects and benefits.

The rise in energy prices combined with economic recession could lead many families back to an energy poverty situation, and the high share of energy in total expenses can affect consumption of other essential goods. According to our results, 6.1 million households lived in deprivation in the affordability dimension in 2017. The recent economic crisis showed the effect of reducing income and increasing energy prices in bringing families to an energy-poor condition (ANÍBAL, 2021; Felicio *et al.*, 2021). The relationship between low-income and vulnerable situations with energy poverty conditions is confirmed in chapter 3.

Moreover, there is still an essential gap in the ownership rates of AC appliances in Brazil. The third study (chapter 4) showed that this could lead energy-poor people to be even more vulnerable under climate change scenarios. Higher temperatures would increase the use of AC appliances, causing energy consumption to rise, as along with the expenses associated with it. As demonstrated in the second study presented here, low-income households are more likely to live under energy poverty, making it challenging to acquire efficient appliances or retrofit their homes to adapt to the effects of climate change.

As demonstrated in chapter 3, people living in energy poverty have the worst household conditions, indicating an inability to adapt their homes to a warming climate. Also, affordability nowadays seems to be the main issue related to energy poverty. Due to warming weather, the rise in energy consumption could increase electricity expenses, putting more people in a vulnerable energy situation. The study on energy poverty did not give significant attention to the role of AC appliances, as the study’s main goal was to understand the historical evolution of the energy poverty metric in Brazil. Besides that, the results demonstrated in chapter 4 highlight that thermal comfort is very relevant for Brazil nowadays. There is a broad consensus about the role of ambient comfort and health

(Jessel, Sawyer and Hernández, 2019), and the exposition of part of the population to the lack of AC and the high energy expenses could affect the way we live and people’s overall wellbeing.

At this point, it is important to highlight that in a country with continental dimensions, like Brazil, different geographical regions have their own characteristics and conditions. Therefore, considering the three studies discussed, two specific regions deserve more attention. States in the North and Northeast regions were the ones that most benefited from LpT program – they had the greater increase in the electrification rates and consequently improvements on HDI. The impacts of LpT corroborate the results observed on MEPI results. The dimension of physical access showed a significant evolution in those regions. However, despite the improvements in HDI due to electrification, there is a persistence of energy poverty conditions. The incidence and intensity of energy poverty are still higher in the rural North than in the other regions. The North and Northeast regions also present the lowest average income and concentrate most people in the first income deciles. In addition, some isolated areas of these regions still lack reliable electricity and suffer from the higher prices of LPG and modern fuels, retail for distribution (Mazzone, Cruz and Bezerra, 2021).

Those regions also present the highest average annual temperatures in the country. Considering a CDD_{wb} of 24ºC used in the third study presented here, space cooling solutions are needed almost all year long. Scenarios of climate change could exacerbate this situation. In the Northeast region, AC ownership rates are significantly lower than in other regions; 15 million households without this appliance are vulnerable to thermal discomfort caused by heatwaves and hot weather. In the North region, despite the higher ownership rates, the affordability and physical dimensions show that the use of such appliances would be limited, especially for those in rural areas and the lowest deciles. Almost all rural households in the first three income deciles do not have AC appliances. In North urban, the rate of AC ownership is only 10% of low-income households. Moreover, these families already expend a high share of their income to pay for energy for their homes. Considering the worst climate scenario of chapter 4 (SWL 4 °C), an increase of 190% in energy consumption is expected. This demand rise could impede income-vulnerable households from properly meeting their cooling needs. More than that, the growth of energy expenses could affect those households' whole basket of consumption.

By associating the findings presented in chapters 2 and 3, evidence is provided that intense consequences of climate change will affect the regions that concentrate most of the poor people in Brazil. People in the lowest deciles will hardly acquire new and efficient appliances to reduce their energy consumption. Therefore, the increasing need for space cooling would impact families' electricity bills, reducing their ability to consume essential goods and affecting directly or indirectly other dimensions of poverty – making them the most vulnerable to live in an energy-poverty situation.

The best characterization of energy poverty risks should be important to define the dimensions of energy poverty and energy vulnerability in future scenarios, especially climate change-related.

The use of thermal cooling appliances requires a reliable and constant supply of electricity, which is not observed in some regions of Brazil. Therefore, analysis considering the reliability of the electrical connection is pointed out as necessary for mapping future risks of energy poverty. Both studies, presented in chapters 2 and 3, show evidence that poverty and energy are correlated to many other aspects of infrastructure and the use of energy is a basic condition for overall development. Results indicate that eradicating energy poverty is possible by identifying and targeting the right social groups with a structured and targeted program.

Successful implementation of LpT, combined with other social programs helped to bring social development for the targeted regions. For the future, comprehensive policies addressing all dimensions of energy poverty identified in chapter 3 could achieve significant social benefits for Brazilian families, which could also be more sustainable in the long-term. The results presented in this work can therefore guide decision-makers to implement better measures to guarantee people's wellbeing under different economic and climate situations. Investments on eradication of energy poverty could be key to the improvement of social development and to achieve SDG goals.

New policies designed should consider regional differences and the risks associates with climate change. Some suggestions are pointed out here:

- Social housing: this could save energy and allow families with low incomes to live in appropriate thermal conditions, if well projected (Triana, Lamberts and Sassi, 2018; González Mahecha *et al.*, 2020; Mazzone, 2020b). The use of efficient homes can be responsible for saving energy and should be considered an important target for the government. It is expected that houses are also designed to attend regional and local particularities to assure low energy costs for the families. Thermal comfort needs focusing on heat stress should be considered in hot regions like Northeast and North. And the effects of low temperatures should be observed in South region. Moreover, social houses should be supplied by low-cost renewable energy systems.

- Onsite power generation to reach isolated areas and poor communities: Some of those communities have limited access to electricity, only few hours a day, or calculated to be used with low energy limits. The use of appliances such as AC would not be possible under those conditions (Mazzone, 2019a; Mazzone, Cruz and Bezerra, 2021). People should be able to use all appliances that are available for them to have a decent living. The trustful energy should be a base for governmental programs such as LpT. Policies need to guarantee that electricity is available all the time and for a low-cost.
- Tarifa Social program: The limit for discounted tariffs is well below Brazilian average (EPE, 2019) and the minimum requirements for decent living (Rao, Min and Mastrucci, 2019a), implying that families with low incomes should be expected to not benefit of overall services that electricity can bring. Energy needs with AC appliances would increase even more electricity use further surpassing the limits.
- *Bolsa-família*: As already observed by (Mazzone *et al.*, 2019), there is an urgent need for adaptation of this income transfer program, and the benefits should follow the increase in LPG prices observed though the country, especially in isolated areas. The new voucher for LPG (Governo do Brasil, 2021) is an important step on this issue and should be explored to assure that families are not so vulnerable to variations in fuel prices.

Nevertheless, many issues are still unresolved due to the complexity of energy poverty and its correlation to many other social objectives. Hence, the proposed methodologies and the findings reported here introduce interesting and new research lines, which can be explored in future studies.

First, to be able to design more appropriate policies to eradicate energy poverty, it is important to understand its drivers. A study focusing on the relations between energy poverty and different social, economic and infrastructure characteristics should be able to answer what features of a household increase its vulnerability to energy poverty conditions and how to avoid it.

Vulnerability to weather conditions should also be further explored in future studies. The index for calculating energy poverty should explore deeply thermal comfort conditions under different climate change scenarios. A study quantifying how many people are vulnerable to the warmer conditions observed in chapter 4 should be addressed. Moreover, it is essential to understand if vulnerable population are able to adapt. For that, an energy poverty index focusing on climate change should include other metrics, such as the thermal efficiency of a house and energy prices under different climate scenarios.Also, this would bring to a discussion on who can afford efficient homes and appliances to guarantee thermal comfort. Governmental efforts should eradicate the thermal inefficiency of social houses and help people with low-income conditions save energy and control their electrical bills.

In addition, considering the social gains observed from the increase in electricity access shown in chapter 2, MEPI benefits could also be observed from this perspective. Quantify how eradicate energy poverty could imply on increase HDI or another social index should be considered.

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ANNEX

ANNEX 1:

a) Descriptive statistics of all the variables inserted in the model

Variables	Min	1st Qu	Median	Mean	3rd Qu	Max
MHDI	0.20	0.39	0.49	0.48	0.57	0.71
MHDI_E	0.04	0.19	0.31	0.32	0.45	0.61
MHDI_L	0.55	0.65	0.71	0.71	0.76	0.85
MHDI_Y	0.33	0.46	0.51	0.51	0.55	0.70
T_LGITH	10.30	54.50	68.68	70.87	92.74	100.00
V_BF	2864	23960	39940	51390	65680	316900

b) Correlation matrix of the model variables

	IDHM	IDHM_E	IDHM_L	IDHM_Y	T_LIGTH	V_BF
IDHM	1					
IDHM_E	0.9764982	1				
IDHM_L	0.8731050	0.8052615	1			
IDHM_Y	0.7972515	0.6733530	0.7399156	1		
T_LIGTH	0.8568461	0.8720774	0.7178726	0.5756068	1	
V_BF	0.5473096	0.5758726	0.4751958	0.3130929	0.5838101	1

ANNEX 2: Rank exponent method

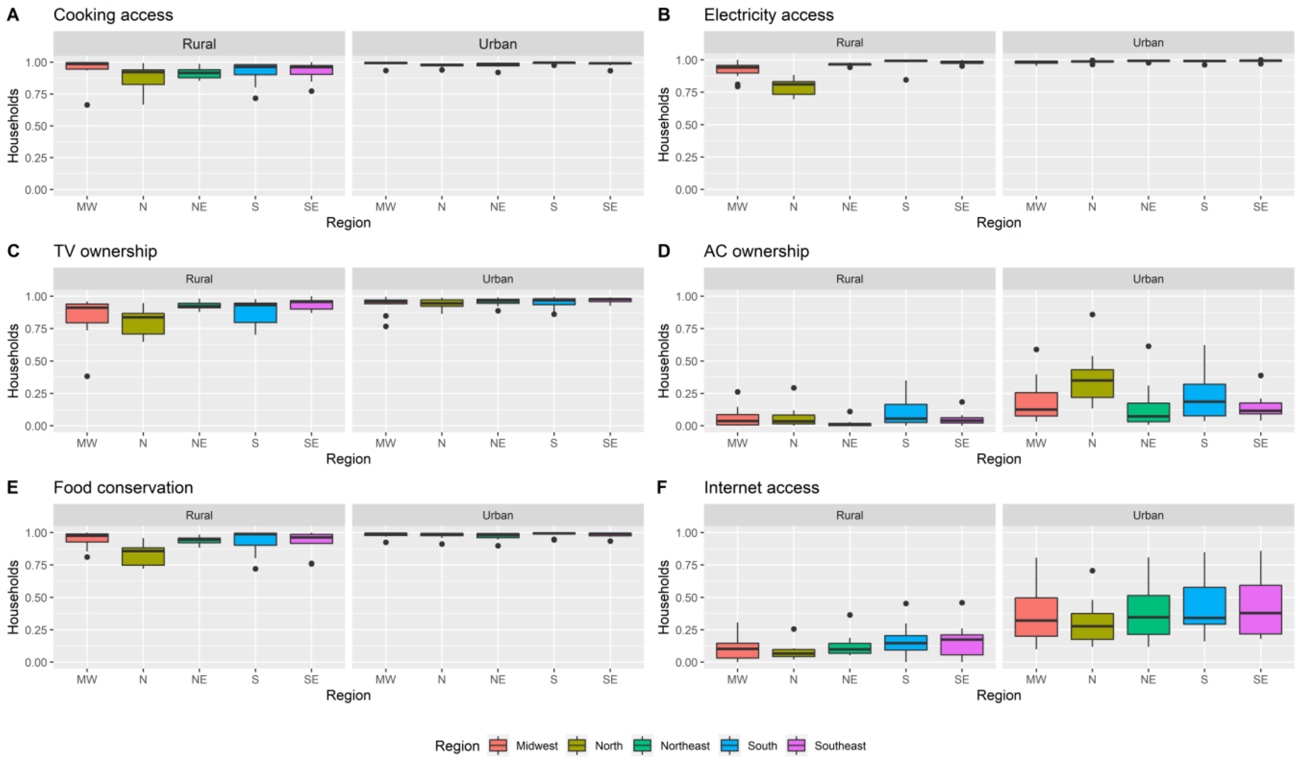
		Rank					
Dimension	**ρ**	phy = 1; ap = 3; aff = 2	phy = 1; ap = 2; aff = 3	phy = 2; ap = 1; aff = 3	phy = 2; ap = 3; aff = 1	phy = 3; ap = 1; aff = 2	phy = 3; ap = 2; aff = 1

Physical Access	0	0.333	0.333	0.333	0.333	0.333	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's 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

ANNEX 3: Energy expenses and its share on total expenditure of a household

	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%)

ANNEX 4: Brazilian heterogeneity



ANNEX 5: 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
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

ANNEX 6

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	44.57	48.72	44.57	37.97	22.34	6.35	2.45	0.82	-	-
Alagoas	13.05	17.36	11.00	8.49	3.10	1.44	-	-	-	-
Amazonas	28.12	38.57	28.12	21.46	9.20	5.56	4.25	2.21	0.41	0.41
Amapá	39.07	39.22	34.86	24.29	13.25	6.49	0.11	-	-	-
Bahia	15.30	20.15	11.47	8.72	1.80	1.16	0.21	-	-	-
Ceará	16.68	19.86	8.85	8.26	1.19	0.45	-	-	-	-
Distrito Federal	11.89	17.79	11.32	10.63	0.89	-	-	-	-	-
Espiríto Santo	9.61	11.40	9.61	9.61	1.52	-	-	-	-	-
Goias	14.29	17.00	13.76	12.54	2.34	1.04	0.17	0.17	-	-
Maranhão	22.80	29.01	22.80	16.19	4.64	3.09	1.90	0.38	0.19	0.19
Minas Gerais	15.28	18.78	11.21	10.03	1.41	0.84	-	-	-	-
Mato Grosso do Sul	13.92	17.70	12.80	12.24	1.07	0.15	-	-	-	-
Mato Grosso	12.62	18.52	11.32	9.96	1.67	0.58	0.05	0.05	0.05	-
Pará	39.59	39.59	32.99	24.48	18.15	5.81	3.20	0.54	0.15	0.06
Paraíba	11.62	16.32	9.58	8.91	1.32	0.83	0.60	0.51	-	-
Pernambuco	13.98	19.36	10.63	9.12	2.07	1.16	0.05	-	-	-
Piauí	20.26	23.84	16.03	13.94	6.41	3.75	0.22	0.22	0.09	0.09
Paraná	12.00	16.76	10.95	9.57	1.43	0.53	0.20	0.12	-	-
Rio de Janeiro	12.26	15.61	10.83	10.35	1.27	-	-	-	-	-
Rio Grande do Norte	13.19	14.31	8.45	7.17	1.29	0.46	-	-	-	-
Rondônia	16.40	23.33	16.40	13.99	1.08	-	-	-	-	-
Roraima	23.33	23.54	23.33	21.76	9.47	0.20	0.20	-	-	-
Rio Grande do Sul	9.79	13.78	8.53	8.02	1.17	0.27	-	-	-	-
Santa Catarina	12.00	15.65	9.98	9.77	0.63	0.31	-	-	-	-
Sergipe	18.96	25.78	16.74	14.56	2.87	1.05	-	-	-	-
São Paulo	11.83	16.08	11.28	10.82	0.24	-	-	-	-	-
Tocantins	21.10	25.95	21.10	17.55	6.81	3.05	2.76	-	-	-

b) Incidence of energy-poverty for different deprivation cut-off sensitivity in urban 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	7.97	13.65	7.50	7.10	0.72	0.12	0.12	-	-	-
Alagoas	10.03	13.54	9.40	8.63	0.90	0.21	0.05	0.05	-	-
Amazonas	14.38	19.97	11.96	10.66	2.61	0.44	0.17	-	-	-
Amapá	10.07	35.21	10.07	7.78	2.80	-	-	-	-	-
Bahia	11.07	15.19	10.47	9.88	0.56	0.33	0.05	-	-	-
Ceará	10.89	14.16	9.44	8.33	1.01	0.29	0.10	0.03	-	-
Espiríto Santo	10.39	12.23	9.93	9.67	0.50	0.11	-	-	-	-
Goias	8.52	11.22	8.52	8.52	1.09	-	-	-	-	-
Maranhão	12.55	16.48	12.55	10.60	1.61	0.67	0.32	0.13	-	-
Minas Gerais	9.33	11.80	8.76	8.47	0.55	0.14	0.08	-	-	-
Mato Grosso do Sul	9.62	13.31	9.53	9.23	0.95	0.07	-	-	-	-
Mato Grosso	10.02	14.19	9.37	9.13	0.81	0.22	-	-	-	-
Pará	15.38	15.67	11.64	10.52	8.95	0.71	-	-	-	-
Paraíba	10.90	14.51	10.56	9.76	0.77	0.27	-	-	-	-
Pernambuco	11.57	14.51	10.36	9.71	0.83	0.15	0.05	-	-	-
Piauí	9.63	12.59	8.82	8.69	1.02	0.22	-	-	-	-
Paraná	11.35	15.28	11.05	10.88	0.87	0.06	0.02	-	-	-
Rio de Janeiro	10.42	12.76	9.86	9.42	0.34	0.20	-	-	-	-
Rio Grande do Norte	10.42	13.18	9.10	8.63	0.38	0.14	-	-	-	-
Rondônia	11.68	21.19	11.42	10.26	0.84	0.17	-	-	-	-
Roraima	15.58	17.34	10.83	8.83	3.80	0.90	0.28	-	-	-
Rio Grande do Sul	9.53	10.92	9.04	8.94	0.14	0.04	0.04	0.04	0.04	-
Santa Catarina	8.51	10.35	8.17	8.03	0.36	0.06	-	-	-	-
Sergipe	10.55	11.97	10.07	9.33	0.57	0.19	0.05	-	-	-
São Paulo	10.11	12.00	9.67	9.51	0.42	0.07	-	-	-	-
Tocantins	13.29	18.65	12.65	9.58	1.38	0.38	-	-	-	-