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Research article

Multidimensional energy poverty in Colombia: A department-level review from 2018 to 2022

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ABSTRACT

This article aims to measure energy poverty in Colombia in its thirty-two departments and its capital city from 2018 to 2022, using a composite approach. To achieve this, a Multidimensional Energy Poverty Index (MEPI) was designed, according to the methodology proposed by Nussbaumer et al. (2012; 2013) [1,2]. Twenty-eight variables were used, which were distributed across seven dimensions, and recorded by the National Quality of Life Survey (ECV, Spanish acronym), administered by the National Administrative Department of Statistics (DANE) of Colombia. In addition, a nested weighting method was used to assign weights within the index. Subjective weights were given to the dimensions, and an entropy method was used for each of the component variables. The results show that energy poverty has an increasing trend in Colombia throughout the period, especially in the municipal capitals. There are significant differences between urban and rural areas in all territories, and the departments located in the most remote areas of the country have a higher energy poverty. This is consistent with the low population density, as well as with off-grid areas. The results obtained will allow decision makers to conduct a preliminary evaluation of the management and effects of the specific public policy programs and plans that have been implemented in the different territories of the country.

1. Introduction

Energy is a resource intimately associated with satisfying human needs and social well-being [1,2]. For Daly & Walton [3], access to energy is what links economic growth, human development, and environmental sustainability. Ensuring access to affordable, reliable, sustainable, and modern energy services (SDG 7) is a goal of the United Nations 2030 Agenda [4] to address poverty, inequality, and environmental degradation. The relationship between SDG 7 and other sustainable development goals becomes evident [5]; such as ending poverty (SDG 1), ensuring sustainable cities and communities (SDG 11), combating climate change (SDG 13), rural development (SDG 2), among others. According to estimates by the International Energy Agency (IEA), after the COVID-19 pandemic, around 760 million people lacked access to electricity, and about 2.3 billion people did not have access to clean cooking facilities and used inadequate fuels for cooking worldwide as of 2022 [6]. In Colombia, according to estimation by the Mining and Energy Planning Unit (UPME, Spanish acronym) of the Ministry of Mines and Energy, for that same year, approximately 1.2 million households lacked access to electricity [7].

Considering the relationship between household energy consumption, economic growth, and human development index [8,9], these figures are alarming. The deprivation experienced by vulnerable individuals in accessing quality energy services is a significant

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problem. Energy-related poverty can affect health, education, productivity, and well-being [10–13]. According to Bouzarovski & Petrova [14], energy poverty can be defined as a problem related to the inadequacy of motive power, deficiencies in end-use, or the consequences suffered by those experiencing energy deprivation, depending on the chosen perspective. For González-Eguino [15], energy poverty manifests in various ways, depending on the specific limitation or deprivation of energy use. Thus, a person can be energy poor from a technological perspective (lack of infrastructure to access services), economic perspective (inability to pay), or physical perspective (lack of minimum energy consumption required to meet needs).

In Colombia, public policy has focused its efforts on reducing the deprivation experienced by households [16–19], from a technological standpoint (by seeking universal coverage of electricity and natural gas services), economic standpoint (through the implementation of cross-subsidy programs in favor of the less privileged), and physical standpoint (by setting a minimum consumption level and quality and continuity targets for the service). However, understanding energy poverty requires the definition of more complex metrics that go beyond mere ideas of access and expenditure [20,21–23]. To date, there is no legal standard or public policy program defining the criteria for determining when a household is considered energy poor in Colombia. Neither the public entities involved in decision-making on energy issues (such as UPME, IPSE, or the Ministry of Mines and Energy) nor DANE have undertaken such a task. The Electricity Coverage Index (ICEE, Spanish acronym) calculated by the UPME [7] is one of the unidimensional instruments used for characterizing the population that will benefit from public policy programs and identifying their needs.

This research primarily aims to address the lack of definition, measurement, and identification of energy poverty in the country. Although there are some specific studies attempting to measure energy poverty in Colombia, due to data scarcity, their results are not truly illustrative of the situation and local needs [24–26], nor do they study the country in comprehensive terms [27]. Therefore, a composite approach to measuring energy poverty (MEPI) was employed intertemporally (from 2018 to 2022) to overcome the subjective deficiencies of unidimensional measures and thus achieve broader and more illustrative findings regarding the energy conditions of the population. Additionally, given the change in methodology proposed by DANE in 2018 for the National Quality of Life Survey (ECV), the data under study covers the entire country and allows for territorial breakdown (in the thirty-two departments and the Capital District), both in urban and rural areas. Before 2018, the ECV identified household locations only at the regional level, which did not allow for proper local-level data review and could lead to biased or unhelpful results. Hence, our results will enable decision-making entities to preliminarily assess the management and effects of specific public policy programs and plans that have been implemented in the country. Moreover, the index proposed in this research can be replicated by the involved entities or other researchers over time (using data provided by the ECV or any other survey) to continue with monitoring and impact evaluation processes.

Therefore, Section 2 presents the context of energy poverty in Colombia. Section 3 reviews the concept of energy poverty and the proposed measurements for its estimation. Section 4 explains the methodology used and the selected data. Section 5 presents the results obtained, and Section 6 discusses them, both at national and departmental levels in certain special cases. Finally, Section 7 addresses the conclusions and policy implications of the estimations made, and new gaps for future research are proposed.

2. Colombian energy context

In 2022, 12.9 % of the Colombian population was in a multidimensional poverty situation [28], although this index has shown a decreasing trend [29]. Of these, 8.7 % of households in municipal capitals (urban areas) and 27.3 % in rural areas were considered poor. According to government data, approximately 1,261,928 households in 2022 still did not have access to electricity services, accounting for 6.9 % of the population [7]. This represents an increase in households without electrical power in the country, as in 2019 there were 1,009,042 (6.03 %). The departments with the lowest electricity coverage rates for 2022 were Vaupés (32.54 %), Vichada (43.03 %), La Guajira (55.74 %), Amazonas (61.77 %), Magdalena (71.57 %), Guainía (73.04 %), and Putumayo (73.21 %). Thus, not only is the principle of universality of the service not being met, but also criteria of efficiency, affordability, and continuity.

According to estimates by DANE, based on the most recent National Household Budget Survey (ENPH, Spanish acronym), 28.7 % of total household expenditures corresponded to housing, water, electricity, and other fuels for the years 2016 and 2017 [30]. Within this division, the estimate related to water, electricity, and other fuels services was approximately 9.5 % of the total average household expenditure. For the years 2006 and 2007, the share of this housing and services component of expenditure represented 20.3 %. By 2021, this share had increased to 41.4 % [31], indicating a growing trend over time. This is particularly alarming when nearly 60 % of households in the country receive just over two minimum legal monthly wages as total average income, and more than half of single-person households (51.7 %) earn less than one minimum monthly wage [32]. In fact, according to estimates by the Latin American Strategic Geopolitics Center (CELAG, Spanish acronym), around 2.4 % of the current per capita income of Colombian households is allocated to monthly electricity payments, and the poorest decile of the population allocates 6.3 % of their income [32]. Additionally, according to data from the Ministry of Mines and Energy, nearly 6 million people still cook their food with firewood [33]. All of this indicates the existence of a gap in access to essential services in Colombia, especially energy-related ones.

In this context, the Superintendency of Public Utilities reported that at least eight of the nineteen companies supplying electricity to users at tension levels 1 (nominal tension below 1 kW) as well as tension levels 2 and 3 (nominal tension equal to or greater than 1 kW and less than 57.5 kW) had a lower service quality indicator for at least one quarter of 2017 compared to 10 years earlier [34]. Also, for 2021, the indicator measuring the average duration in annual hours of interruptions perceived by users connected to the electricity system (SAIDI, Spanish acronym) and the indicator measuring the average number of times a year interruptions occur (SAIFI, Spanish acronym) recorded values of 29.6 h and 38.2 interruptions per year respectively [35], still exceeding the public policy targets set by the Energy and Gas Regulation Commission (CREG, Spanish acronym) for 2023: 25.0 and 32.0, respectively (Resolution 010 of 2018 of the CREG). Naturally, interruptions in energy service provision are affecting different regions of the country, especially in rural and off-grid areas, exacerbating conditions of energy poverty.

Since 2015, Colombia has been preparing itself for an energy transition. This demands an evaluation of the role played by the social dimension in public policies, particularly concerning energy poverty [36]. Energy transitions must be fair, recognizing and addressing the needs of the most vulnerable and offering them appropriate solutions. Nonetheless, in the country, energy transition programs are not proposed to impact households without electrical coverage. In fact, objectives 1 and 4 of the pact for the quality and efficiency of public services of the National Development Plan 2018–2022 simply aimed to expand the existing electricity network, not implementing new clean generation options [37]. On the other hand, the National Development Plan 2022–2024, while referring to the need to implement energy transition strategies to ensure social justice, does not indicate the legal and financial decisions to reduce energy poverty [38]. The investment required to achieve universal electricity service coverage, according to the indicative expansion plan 2019–2023 prepared by the Mining and Energy Planning Unit, is approximately $3.5 billion dollars, with 37 % allocated to expanding the National Interconnected System, 14 % for isolated microgrid and energy community solutions, and the remaining 49 % for individual isolated photovoltaic solutions [39].

Although, by constitutional mandate, utilities in Colombia are associated with the social purpose of the State [40], energy poverty has not been addressed normatively. In other words, there is no legal norm that explicitly indicates the problem associated with energy poverty, nor are there public policies that offer a diagnosis of its causes, the current state of the population, and its possible solutions. Only some tariff policy actions have been taken that, from the perspective of distributive justice, contribute to mitigating social asymmetries [41]. Institutionally, factors contributing to the generation of energy gaps in Colombia have been identified, such as: (i) inequality among territorial entities due to resource allocation and participation in the general system of royalties [42]; (ii) the difference between the off-grid areas and the National Interconnected System (SIN, Spanish acronym) in terms of tariffs and quality of energy service, with off-grid areas always presenting low compliance with indicators [43]; (iii) the excessive centralization of energy policy planning and regulation that doesn't foresee the situation in the territory and promotes discoordination among national, departmental, and municipal governments to jointly address energy deficiencies; (iv) economic inefficiency for concessionaire investors in off-grid areas to the point that the WACC formula of concession contracts differs depending on the greater risk; and (vi) the dispersion of users in off-grid areas making the market difficult.

3. Literature review

3.1. The concept of energy poverty

The first approach to the concept of energy poverty was in the 1980s through the notion of 'fuel poverty', based on a lack of access to fuel [44]. Fuel poverty was considered as a subsistence factor and was associated with the impossibility of buying fuel and therefore, not being able to heat one's home [45]. Energy poverty was related to the resources a household had to access energy services [46] and the fair price they should be offered to buy energy [47]. The emphasis on heating services in countries with seasonal climates has been highlighted, but it is not relevant to tropical countries, where household energy needs are focused on factors such as lighting, food preservation or cooking. Heating, as the only reference criterion, is too simplistic and ignores social, cultural, and geographic variables that can also explain this phenomenon.

As studies began to be conducted in developing countries, the concept began to change from fuel poverty to energy poverty. The latter more accurately examines the conditions a household lives in, in terms of access to energy services and its ability to use them to improve quality of life, rather than an inability to pay for them [14,48,49]. These factors consider energy poverty from a subjective perspective and use sociodemographic parameters. Thus, multidimensional energy poverty involves the inclusion of various interrelated aspects that affect households' access to and appropriate use of energy. It moves away from an approach to poverty that solely focuses on the inability to pay for energy services, to also study other factors such as housing quality, household energy efficiency, residents' health and well-being, as well as broader social and economic aspects that influence the energy vulnerability of communities.

3.2. Measuring energy poverty

Energy poverty has been measured using individual or composite approaches. Unidimensional indicators are usually based on household financial information. Boardman [50] proposed the 10 % indicator for the UK, in which a household is considered energy poor if its energy expenditure exceeds 10 % of its income. Hills [51,52] created the Low-Income High Cost (LIHC) indicator to identify households that pay more for fuel than the national average, but whose residual income after fuel expenditure is below the official poverty line. Moore [53] constructed the Minimum Income Standard (MIS) indicator, in which a household is in energy poverty if (after discounting its actual housing and subsistence costs), it does not have sufficient income to cover its total fuel costs. Castaño-Rosa et al. [54] employed the 2 M indicator, in which a household is estimated to be energy poor when it pays more than twice the median, mean, median share, and mean share of its income, on energy services.

Although individual indicators have been widely used, they are criticized for their lack of empirical justification [55], their neglect of the existing dependence on market prices [56–59], and their narrow focus on the problem [60,61]. Their major advantage is that they are adaptable to national standards and are objective measurements [62].

For the composite approach, Nussbaumer et al. [20,63] proposed the design of the MEPI which uses the methodology of the Oxford Poverty and Human Development Initiative (OPHI) [64]. This index has been used to assess energy poverty in various countries across Latin America [65], Africa and Asia [66], including Ecuador [67], Chile [68], Brazil [69], Ghana [70], Ethiopia [71], Kenya [72], South Africa [73,74], Uganda [75], Mozambique [76], Nigeria [77,78], Senegal and Togo [79], Pakistan [80], India [81,82], Bangladesh [11,83,84], Tajikistan [85], the Philippines [86], Indonesia [87], Sri Lanka [88], and Vietnam [89], as well as Poland [90], China [91–93], and Japan [94]. However, composite measurement studies are not limited to the MEPI. According to Siksnelyte-Butkiene et al. [62], Siksnelyte-Butkiene [95], and Rizal et al. [87], Table 1 provides some examples of composite indicators used in the literature for assessing energy poverty.

In Colombia, there're studies that have measured energy poverty. Cabello Eras et al. [27] studied inequality in electricity consumption based on data obtained for the years 2010–2019. The research focused on electricity consumption per capita and the Gini coefficient. Although the research is broken down at departmental level, the departments of Guaviare, Putumayo, Amazonas, Guainía, Vaupés, and San Andrés were excluded from the study. Hernández et al. [24], Pérez Gelves [25], and Pérez Gelves et al. [26] opted for a composite approach when designing the MEPI for Colombia, limiting it to the DANE statistical regions (Caribbean, Central, Eastern, Pacific, Amazon-Orinoquia and San Andrés), as well as to some departments (Antioquia and Valle del Cauca) and the Capital District (in its municipal capital). These territorial divisions have truly heterogeneous characteristics. This is not only because of their demographics, but also because they encompass different jurisdictions and administrative structures, and differential technical conditions. Some of these territories belong to the SIN, while others are part of the off-grid areas, which could potentially introduce bias into the results. For example, the Pacific region includes the departments of Cauca, Nariño and a large part of Chocó, whose individual needs and development differ substantially. Only the work financed by Inclusión S.A.S. & Promigas S.A. E.S.P [102]. estimated a MEPI for Colombia by departments for the year 2022.

4. Data and methodology

4.1. Dimensions and variables

The analysed data for the design of the MEPI for Colombia were obtained by the DANE through the National Quality of Life Survey (ECV, Spanish acronym) for the years 2018–2022. In fact, this same source of information was employed in previous studies [24,102]. The ECV aims to measure the living conditions of the population and its access to basic goods and services such as housing, education, health, employment, and social security. To do so, it uses a representative sample of households in Colombia to obtain information on the quality of life and well-being of the population. The sample is randomly selected and stratified, which means that households from different socioeconomic strata and regions of the country are chosen to ensure the representativeness of the sample nationwide.

Since 2018, the ECV has had a global scope, capturing information from all thirty-two departments of Colombia and Bogotá, including urban and rural areas. Consequently, the sample sizes for the years 2018, 2019, 2020. 2021, and 2022 under study were 88,713, 93,161, 87,659, 88,723, and 87,878 households, respectively. Approximately half of the surveyed households were from municipal capitals (urban areas), while the remaining belonged to other populated centres and rural areas. For the estimation of the MEPI, only data provided by households indicating they cooked their own food, and thus had responded to all selected variables were utilized. The total number of households per year included in the sample used to construct the MEPI was 86,577 for 2018, 90,649 for 2019, 86,135 for 2020, 86,931 for 2021, and 86,509 for 2022, representing approximately 97.0 % of the total ECV sample per year. On average, for this same period, the survey included 316 questions (variables) per year administered to randomly selected households at the household level. This implies a high or, in any case, medium granularity of the ECV.

This research employed the same dimensions developed by Nussbaumer et al. [20] and Mendoza et al. [86] to measure multidimensional energy poverty. However, the mobility and temperature regulation dimensions were added following Qurat-ul-Ann & Mirza [80] and Hou et al. [103]. The same indicators and variables were also adopted for the additional dimensions. Appendix 1 presents a comparison of the dimensions and variables used in the different studies.

Finally, twenty-eight variables were selected from the ECV and distributed in each of the proposed dimensions (Table 2). All are binary categorical variables, so their values can be interpreted as the possession of an asset or service (whose value is 1), or the lack of (whose value is 0). For example, a family could indicate in the ECV whether their household had electricity or not. They could also state if they had a refrigerator or other electrical appliances, as well as internet, television, and a landline. It was also possible to identify whether the household had a modern kitchen (exclusive space for cooking) and whether it used modern fuel for cooking food. In accordance with the recommendations by PNUD [104] for the design of multidimensional poverty indices, financial variables were not included in this research. In fact, there are studies that have shown how financial measures can be imperfect predictors of non-financial multidimensional measures [105–110].

Table 1
Other composite indicators of energy poverty identified by Siksnelyte-Butkiene et al. [62] and Siksnelyte-Butkiene [95].

Composite indicators	Ref.
Structural EP Vulnerability Index (SEPVI)	[96]
Fuel Poverty Index (FPI)	[59]
Energy Vulnerability Composite Index (EVCI)	[97]
Energy Poverty Index (EPI)	[98]
Energy Development Index (EDI)	[99]
Total Energy Access (TEA)	[100]
Multi-Tier Framework (MTF)	[101]

Table 2
Dimensions and indicators used in the MEPI.

Dimension (weight)	Indicator	Variable	What is the problem?	Poor if …
Lighting (0.25)	Access to electricity for a range of services	Access to electricity and lighting from the public energy service	No decent conditions for the development of human capital	No access to electricity
Food cooking (0.25)	Modern kitchen fuel	Type of fuel for cooking	Concentration of pollutants (suspended particles such as ash, soot, smoke, metallic elements, etc.) associated with inadequate energy sources that affect health	Uses traditional fuels (such as wood and charcoal) or other non-clean fuels (such as oil, kerosene, gasoline, and waste material)
		Access to natural gas service connected to the public network		No access to natural gas service
	Risk of poor air quality indoors	Modern kitchen in the home		No dedicated room for cooking inside the home.
		Has an electric or gas stove		Does not have an electric or gas stove
		Has an electric or gas oven		Does not have an electric or gas oven
Services using home appliances (0.10)	Ownership of home appliances	Has a washing machine	Lack of time to carry out daily chores	Does not have a washing machine
		Has a refrigerator		Does not have a refrigerator
		Has an iron		Does not have an iron
		Has a microwave		Does not have a microwave
Communication (0.10)	Access to communication devices	Someone in the home owns a cellphone	Lack of opportunities for household members to participate in activities that are socially and culturally enriching.	Nobody in the home owns a cellphone
		Has a landline		Does not have a landline
		Has a desktop computer		Does not have a desktop computer
		Has a laptop		Does not have a laptop
		Has a tablet		Does not have a tablet
		Has internet		Does not have internet
Entertainment and education (0.10)	Ownership of devices used for entertainment and education	Has a conventional color TV		Does not have a conventional color TV
		Has an LCD, plasma, or LED TV		Does not have an LCD, plasma, or LED TV
		Has a cable or satellite TV subscription		Does not have a cable or satellite TV subscription
		Has a video player (DVD, blue ray, etc.)		Does not have a video player (DVD, blue ray, etc.)
		Has an audio player		Does not have an audio player
		Has a digital music, video, and image player (mp3, mp4, iPod)		Does not have a digital music, video, and image player (mp3, mp4, iPod)
		Has a video game console (Play Station. X-BOX. Wii. PSP. Nintendo. Gameboy. etc.)		Does not have a video game console (Play Station. X-BOX. Wii. PSP. Nintendo. Gameboy. etc.)
Temperature regulation (0.10)	Ownership of space heating and cooling devices	Has air-conditioning	Lack of opportunities for household members to have adequate body and space temperatures	Does not have air-conditioning
		Has an electric fan or handheld fan		Does not have an electric fan or handheld fan
		Has an electric or gas water heater		Does not have an electric or gas water heater
Mobility (0.10)	Access to private transport	Has a car	Lack of transportation possibilities for household members	Does not have a car
		Has a motorbike		Does not have a motorbike

4.1.1. Lighting dimension

Household lighting (relative to its connection to the electric power service), is a substantial element in determining poverty status [111]. However, the discussion cannot stop there. Therefore, the first variable used to measure the energy poverty of households was their connection to the utility electricity service.

4.1.2. Cooking dimension

Cooking is one of the most basic household needs and is an issue discussed in this type of studies [88,112]. According to the World Health Organization [113,114], ensuring access to clean fuels and technologies is crucial for preserving health and maintaining indoor air quality. Clean fuel options such as solar energy, electricity, biogas, natural gas, liquefied petroleum gas (LPG), and alcohol fuels, including ethanol, play a vital role in achieving this objective [115]. Nonetheless, approximately 2.3 billion people globally, constituting around one-third of the global population, rely on rudimentary cooking methods such as open fires or inefficient stoves fuelled by kerosene, biomass (wood, animal dung, and crop waste), and coal [114]. As might be expected, in places where a connection to natural gas and electricity networks is not easy, families often opt for unsustainable cooking fuels. This reliance on polluting fuels poses significant health risks and contributes to environmental degradation. If the household does not have optimal space for food preparation and does not burn fuel correctly it can have consequences, such as respiratory diseases [116]. Therefore, it is imperative to acknowledge the plight of individuals and households compelled to use such harmful fuels [117,118]. Hence, efforts to make visible and support these households are essential in mitigating the adverse effects of energy poverty and promoting sustainable development [81].

For the construction of the MEPI, variables were used to measure the type of fuel used in the household for cooking food, as well as the possibility of accessing natural gas service as a clean and economical fuel par excellence [82]. Furthermore, to assess the risks of indoor pollution, it was identified whether households had an exclusive space for cooking and if they had appliances that guarantee the reduction of contamination.

4.1.3. Services using home appliances dimension

When measuring energy poverty, it is reasonable to incorporate variables related to the ownership of appliances, as they indirectly reflect the household's financial means to possess assets that enable timesaving in activities and improve quality of life. This has been noted in multiple previous studies [119–121]. For instance, a household equipped with refrigeration services can store perishable foods for longer periods. Similarly, the use of microwaves allows household members to heat their food quickly, adequately, and cleanly. For the present study, we used these two variables and added the ownership of a washing machine and iron, in line with the literature [80,103].

4.1.4. Communication dimension

In accordance with the literature [70,86,103], the dimension of communication was incorporated using the same variables. These include the ability to use a mobile phone (if any household member owns one), having a landline telephone service and internet access, as well as the electronic devices that would enable their use (desktop computer, laptop, and tablet).

4.1.5. Entertainment and education dimension

As maintained by Nussbaumer et al. [20] and Qurat-ul-Ann & Mirza [80], along with the use of household appliances to measure energy poverty, entertainment and education services are relevant as they reveal the access that household members have to leisure activities and even acquiring new knowledge. The variables typically used by previous research were employed, such as owning a TV and having a cable or satellite TV subscription, and additional variables were added due to the high granularity of the ECV. These new variables focused on the means of entertainment, such as owning a video player, video game console, or audio player.

4.1.6. Temperature regulation dimension

Given the economic difficulties that low-income households face in accessing energy services that provide adequate thermal comfort, climate change disproportionately affects these vulnerable individuals. In fact, since 1990, the energy demand related to indoor cooling of households has tripled [122], and it is expected to continue increasing in developing countries with severe climatic conditions [123]. There is empirical evidence that high temperatures in densely populated areas can lead to increased mortality among the most vulnerable [124,125]. Therefore, research has focused on studying the causes and consequences of potential household cooling gaps [126,127]. Additionally, the deprivation of access to adequate heating and cooling is already recognized as an issue that must be measured through monitoring energy poverty for the formulation of public policies [101]. Feeny et al. [89], for instance, assessed the impact of temperature shocks on multidimensional energy poverty in Vietnam for the years 2010–2016.

In Colombia, despite not being a seasonal country, authorities have taken temperature into consideration for public policy formulation (Resolution 335 of 2004 of the UPME), given its variety of thermal floors [128] and abrupt climate variation [129]. This is especially relevant since recent research has found that the majority (70.0 %) of social interest housing financed by the government for poor people in Colombia lack adequate thermal comfort conditions [130]. Therefore, following Bezerra et al. [69] and Mendoza et al. [86], the dimension of temperature regulation in households was incorporated, using three variables related to the ownership of air conditioning, fans, and water heaters in the shower.

4.1.7. Mobility dimension

In prospective mobility studies in Colombia, there is a projected growth in the automotive fleet directly associated with public policies aimed at reducing the pent-up demand for access to private vehicles [131]. However, more than half of the population uses mass transportation, which comes with complications in mobility and connectivity options. In fact, Colombia ranks 92nd out of 141 countries in terms of transportation infrastructure, evaluating aspects such as efficiency, connectivity, density, and road quality [132]. Data on lack of energy connectivity and lack of transportation connectivity overlap and are linked as dimensions of multidimensional poverty [133]. It is estimated that in Colombia, the most vulnerable sector regarding mobility issues are rural areas [134]. Therefore, following Qurat-ul-Ann & Mirza [80] and Hou et al. [103], this dimension was incorporated, and two variables related to the ownership of private transportation means were included.

4.2. Weightings and estimates

To design the MEPI for Colombia by department, nested weights were used with a combination of subjective and objective methods of assignment. Each dimension was given a discretionary weight according to the evidence and the literature, the entropy method was then used to distribute the weighting among its different variables. The use of nested weights has been widely used in multidimensional poverty indices [104] and the entropy method has also been used to assign weights in MEPIs [91,103,135,136]. To avoid bias, we opted for a combination of the methods to respect the weight of each dimension in the index, and to ensure statistical objectivity in the distribution of the weights among the variables.

The entropy method assesses the level of disorder in a system. The greater the distribution of the data, the lower the entropy of the information for each indicator. Therefore, the greater the information provided, the greater its impact with respect to comprehensive assessment, giving the information greater weight, and vice versa [137,138]. The steps used to assign the weights in the index are summarized below (for example, the estimates of the weights w_j for the year 2018 are presented in Appendix 2):

1. To carry out the discretionary distribution of the weights (α) among the seven different dimensions. Thus, takes the value 0.25 for lighting and food cooking dimensions, and value 0.1 for all the rest (Table 2).

The literature typically assigns higher weighting (0.2) to the dimensions of lighting and food cooking in the multidimensional energy poverty index compared to other dimensions [20,63,11,70,72,80,81,84–86]. In fact, some studies only measure these two dimensions to assess energy poverty [82]. We estimated an even higher weighting (0.25) for them given that public policies in Colombia have mainly focused on expanding electricity coverage and achieving the substitution of firewood and other polluting fuels with clean energies [16–19]. In fact, post-COVID-19, there is empirical evidence suggesting that there are households connected to the electricity grid but still use non-clean fuels for cooking [139].

2. To calculate the entropy value for each j^{th} variable according to the ratio, or if desired, the probability (p) of its (0. 1) values:

$$e_j = \sum_{i=0}^{1} p_{ij}\, ln \frac{1}{p_{ij}} = -\sum_{i=0}^{1} p_{ij} \ln p_{ij}$$

3. To calculate the variation coefficient for each j^{th} variable:

$$d_j = 1 - e_j$$

4. To calculate the weight of each j^{th} variable, considering its respective nested weighting which can take the values 0.25 and 0.1, depending on the dimension to which the variable belongs:

$$w_j = \alpha \left(\frac{d_j}{\sum d_j} \right)$$

As mentioned, energy poverty is measured using the methodology proposed by Nussbaumer et al. [20] and Alkire & Foster [64]. To achieve this, a matrix $Y = \left[y_{ij} \right]$ or matrix of achievements (possessions) was created for i households across each of the j variables for each year under study. Each row vector $y_i = (y_{i1}, y_{i2}, y_{i3} \ldots, y_{28})$ represents the achievements of household i across all dimensions. Meanwhile, each column vector $y_j = \left(y_{1j}, y_{2j}, y_{3j} \ldots, y_{nj} \right)$ shows the distribution of achievements in the variable j across households. This information was used to design the G_{ij} matrix or household deprivation matrix, where each element g_{ij} is defined as $g_{ij} = w_j$ when the i^{th} household does not possess the j^{th} variable; otherwise $g_{ij} = 0$. With this data, the column vector C equivalent to the weighted sum of deprivations for each i^{th} household, $C_i = \sum_{j=1}^{28} g_{ij}$, was constructed. A poverty cut-off line of $k = 0.5$ was employed, which assumes that each i^{th} household is considered energy-poor if $C_i \geq k$. MEPI is calculated as the product of the energy poverty headcount ratio (H) and the average intensity of deprivation of the energy-poor (A), where q is the number of energy-poor households; n is the total number of households; and $C_i(k)$ is the censored value of the sum of deprivations for each i^{th} household, such that $C_i(k) = 0$ when $C_i < k$ and $C_i(k) = C_i$ when $C_i \geq k$.

$$\text{MEPI} = H \times A = \frac{q}{n} \times \frac{\sum_{i=1}^{n} C_i(k)}{q} = \frac{\sum_{i=1}^{n} C_i(k)}{n}$$

According to Alkire et al. [140], selecting the cut-off line k is an evident normative decision. To cite just a few examples, empirical works have used values such as $k = 0.2$ [141,142], $k = 0.3$ [20,63], $k = 0.33$ [82], $k = 0.4$ [90], $k = 0.5$ [77], and $k = 0.6$ [78] as limits for measuring poverty. For the present study, the cut-off line was defined as $k = 0.5$. Thus, a household is considered energy-poor if it has a weighted count of deprivations equivalent to not having access to electricity, as well as being unable to cook food cleanly (either due to lack of clean fuel or the presence of air pollution risks). Alternatively, it means having one of these dimensions deprived (which were weighted more significantly) and two and a half of the others, with a weight α equal to 0.1 (such as communication, services using appliances, and education and entertainment).

Since the ECV made it possible to differentiate whether the surveyed household was in a capital city (where the administrative headquarters of the respective municipality is located) or in other population centres (such as police stations, hamlets, which represent non-municipalized areas, and include rural areas), the MEPI was estimated for each of these areas, and for the total of each department. An energy poverty gap was also estimated between the two zones (except for the island department of San Andres where data is only available for the main cities).

5. Results

According to the methodology described above, the MEPI was designed for Colombia (by departments) from 2018 to 2022. If the value of the score obtained was high, it means that the multidimensional energy poverty was more severe, and vice versa. The estimates of adjusted headcount or incidence (MEPI) for each area (municipal seats, small towns and rural areas, and total) by department are reflected in Table 3. The more intense the red color is, the more severe energy poverty is according to the area. The more intense the green color is, the lower the estimated poverty level. Nationally, the MEPI showed an upward trend (Fig. 1), indicating that the situation has worsened over time. The same occurred in all municipal seats. In the other population centres and in rural areas, there was a slightly decreasing trend. The results are consistent with the Electricity Coverage Index (ICEE, Spanish acronym) calculated by the UPME [7], as the departments with lower coverage (Vaupés, Vichada, La Guajira, Amazonas, Guainía, and Putumayo) present higher scores of multidimensional energy poverty.

MEPI score reflects the percentage of weighted deprivations experienced by energy-poor households in a specific society (for example, according to their territorial location within a department and in urban or rural areas) relative to the total potential energy deprivations that the society could experience [143]. Table 4 and Fig. 2 present the values obtained for the adjusted headcount (MEPI), the energy poverty headcount ratio (H), and the average intensity of deprivation of the energy-poor (A) at the national level for each year of study. On average, 48.95 % of households in the samples are considered energy-poor, indicating acute energy poverty. At the level of municipal capitals and rural areas, on average, 28.09 % and 71.85 % of households, respectively, experience acute energy poverty during the study period. Of these, 62.20 % of energy-poor households at the national level suffer deprivations in at least 50 % of the total dimensions. This percentage is lower in municipal capitals (56.15 %) but higher in small towns and rural areas (64.77 %).

The results of the MEPI at the departmental level for the year 2022 are relatively consistent with the estimates made by Inclusión S. A.S. & Promigas S.A. E.S.P [102]. regarding the ranking of territories with the highest energy poverty. There are only some interesting discrepancies concerning the departments of Casanare, Córdoba, Cauca, and Antioquia. The first two record significantly lower levels of energy poverty in terms of the national average in our study, placing them in a better position compared to other territories. The latter two record significantly higher estimates. These differences must be associated with the dimension employed by Inclusión S.A.S. & Promigas S.A. E.S.P [102]. regarding the energy connection status of educational institutions, early childhood care centres, and banking facilities in the territory, aspects not reviewed in this paper.

Additionally, the MEPI was estimated for the years 2018, 2020, and 2022 for the statistical regions defined by DANE (Table 5): Caribbean (comprising the departments of Atlántico, Bolívar, Cesar, Córdoba, La Guajira, Magdalena, and Sucre), Central (comprising Caldas, Caquetá, Huila, Quindío, Risaralda, and Tolima), Eastern (comprising Boyacá, Cundinamarca, Meta, Santander, Norte de Santander, and the rural area of Bogotá), Pacific (comprising Chocó, Cauca, and Nariño, excluding Valle del Cauca), Amazon-Orinoquia (comprising Amazonas, Arauca, Casanare, Guainía, Guaviare, Putumayo, Vaupés, and Vichada), San Andrés, Bogotá (in its municipal seats), Antioquia, and Valle del Cauca. Our results are consistent with the research conducted by Hernández et al. [24], Pérez Gelves [25], and Pérez Gelves et al. [26]. Particularly, regarding the latter article focused on the years 2018 and 2020, our estimations record a higher MEPI for the Pacific and Amazon-Orinoquia regions. This can be explained by the high scores obtained by the departments that make up these regions and the impact that the inclusion of the dimensions temperature regulation and mobility can have in these territories, especially in the eastern part of the country, given its warm and humid climates, as well as the difficulties present in traveling by land vehicles in the Chocó.

Given that estimates of multidimensional energy poverty can be interpreted as a weighted sum of deprivations experienced by a proportion of the population according to a poverty cut-off line, it is possible to decompose these scores at the level of each dimension, indicator, and variable. This, as proposed by Qurat-ul-Ann & Mirza [80], is useful for decision-making and implementation of specific public policies for each department and area (municipal capitals or rural areas) under study. The contribution of each selected

Table 3
Multidimensional Energy Poverty Index for Colombia by department (2018–2022).

Department	Area	2018	2019	2020	2021	2022	Mean
Amazonas	Total	0.4367	0.4831	0.4555	0.4293	0.4304	0.4470
	Municipal seats	0.2273	0.3069	0.3009	0.2566	0.3227	0.2829
	Small towns and rural areas	0.6581	0.6548	0.6675	0.6771	0.6068	0.6529
Antioquia	Total	0.2095	0.2170	0.2573	0.2599	0.2644	0.2416
	Municipal seats	0.0796	0.1070	0.1430	0.1319	0.1401	0.1203
	Small towns and rural areas	0.3638	0.3439	0.3604	0.3723	0.3687	0.3618
Arauca	Total	0.2957	0.3258	0.3058	0.3017	0.3093	0.3076
	Municipal seats	0.2189	0.2404	0.2281	0.2259	0.2549	0.2336
	Small towns and rural areas	0.4014	0.4027	0.3927	0.3879	0.3711	0.3912
Atlántico	Total	0.2056	0.2711	0.2329	0.2598	0.2296	0.2398

	Municipal seats	0.0722	0.1249	0.1085	0.1270	0.1029	0.1071
	Small towns and rural areas	0.3615	0.4359	0.3698	0.4097	0.3715	0.3897
Bogotá	Total	0.1226	0.1548	0.1250	0.1711	0.1439	0.1435
	Municipal seats	0.0265	0.0369	0.0560	0.0565	0.0572	0.0466
	Small towns and rural areas	0.2681	0.3904	0.2287	0.3753	0.2947	0.3114
Bolivar	Total	0.3119	0.3540	0.3348	0.3444	0.3124	0.3315
	Municipal seats	0.1497	0.2115	0.2039	0.1784	0.1621	0.1811
	Small towns and rural areas	0.5287	0.5532	0.4849	0.5388	0.4853	0.5182
Boyacá	Total	0.2536	0.3111	0.2743	0.2950	0.2567	0.2782
	Municipal seats	0.0571	0.1438	0.0916	0.0949	0.0749	0.0924
	Small towns and rural areas	0.4744	0.4944	0.4722	0.4867	0.4269	0.4709
Caldas	Total	0.1837	0.2399	0.1888	0.2174	0.1961	0.2052
	Municipal seats	0.0469	0.1185	0.0756	0.0622	0.0686	0.0744
	Small towns and rural areas	0.3438	0.3847	0.3239	0.3785	0.3350	0.3532
Caquetá	Total	0.3603	0.4139	0.3621	0.3646	0.3746	0.3751
	Municipal seats	0.1924	0.2491	0.2209	0.1741	0.2208	0.2114
	Small towns and rural areas	0.5683	0.5885	0.5005	0.5569	0.5278	0.5484
Casanare	Total	0.1963	0.2629	0.2085	0.2361	0.2148	0.2237
	Municipal seats	0.0886	0.1282	0.1085	0.1515	0.1375	0.1229
	Small towns and rural areas	0.3394	0.3950	0.3239	0.3377	0.3039	0.3400
Cauca	Total	0.3200	0.3820	0.3554	0.4102	0.3900	0.3715
	Municipal seats	0.1328	0.2511	0.1973	0.2186	0.2034	0.2007
	Small towns and rural areas	0.5332	0.5191	0.5029	0.5583	0.5258	0.5279
Cesar	Total	0.2703	0.3130	0.2991	0.3189	0.2996	0.3002
	Municipal seats	0.1001	0.1489	0.1501	0.1679	0.1580	0.1450
	Small towns and rural areas	0.4707	0.4983	0.4471	0.4639	0.4315	0.4623
Córdoba	Total	0.2903	0.3163	0.3132	0.3280	0.3156	0.3127
	Municipal seats	0.1251	0.1320	0.1313	0.1349	0.1573	0.1361
	Small towns and rural areas	0.4696	0.5127	0.5004	0.5308	0.4796	0.4986
Cundinamarca	Total	0.1718	0.2277	0.2048	0.2112	0.1790	0.1989
	Municipal seats	0.0405	0.1234	0.0922	0.0874	0.0757	0.0839
	Small towns and rural areas	0.3125	0.3334	0.2811	0.3035	0.2510	0.2963
Chocó	Total	0.3818	0.4577	0.4749	0.5163	0.4607	0.4583
	Municipal seats	0.1984	0.3338	0.3119	0.3789	0.3470	0.3140
	Small towns and rural areas	0.5728	0.5978	0.6257	0.6420	0.5632	0.6003
Guainía	Total	0.5289	0.5795	0.6109	0.6133	0.5616	0.5788
	Municipal seats	0.3258	0.3683	0.4013	0.4034	0.3763	0.3750
	Small towns and rural areas	0.7319	0.7734	0.8326	0.8247	0.7654	0.7856
Guaviare	Total	0.3565	0.4133	0.3879	0.4142	0.4188	0.3981
	Municipal seats	0.1522	0.2303	0.2524	0.2716	0.3101	0.2433
	Small towns and rural areas	0.6000	0.5856	0.5413	0.5861	0.5407	0.5707
Huila	Total	0.2245	0.2708	0.2318	0.2329	0.2143	0.2349
	Municipal seats	0.0736	0.1141	0.0963	0.0928	0.1008	0.0955
	Small towns and rural areas	0.4162	0.4465	0.3720	0.3754	0.3289	0.3878
La Guajira	Total	0.4924	0.4848	0.4995	0.5509	0.5183	0.5092
	Municipal seats	0.2067	0.2156	0.2074	0.2284	0.1916	0.2099
	Small towns and rural areas	0.8021	0.7798	0.7989	0.8375	0.7977	0.8032

Magdalena	Total	0.3062	0.3388	0.3256	0.3305	0.3272	0.3256
	Municipal seats	0.1403	0.1794	0.1882	0.1818	0.1910	0.1762
	Small towns and rural areas	0.4932	0.5225	0.4865	0.4986	0.4829	0.4967
Meta	Total	0.2058	0.2252	0.2342	0.2455	0.2134	0.2248
	Municipal seats	0.0678	0.0909	0.0798	0.1141	0.0948	0.0895
	Small towns and rural areas	0.3643	0.3669	0.3646	0.3739	0.3329	0.3605
Nariño	Total	0.3284	0.3689	0.3447	0.3486	0.3432	0.3468
	Municipal seats	0.1742	0.2507	0.2312	0.2304	0.2138	0.2201
	Small towns and rural areas	0.4987	0.5063	0.4607	0.4714	0.4663	0.4807
Norte de Santander	Total	0.3036	0.3040	0.2837	0.3098	0.2731	0.2948
	Municipal seats	0.1292	0.1656	0.1580	0.1771	0.1327	0.1525
	Small towns and rural areas	0.4880	0.4703	0.4245	0.4567	0.4299	0.4539
Putumayo	Total	0.4023	0.4710	0.4174	0.4448	0.4367	0.4344
	Municipal seats	0.2549	0.3446	0.2915	0.2803	0.3122	0.2967
	Small towns and rural areas	0.5982	0.5911	0.5555	0.6135	0.5649	0.5847
Quindío	Total	0.1423	0.1702	0.1754	0.1721	0.1586	0.1637
	Municipal seats	0.0574	0.0831	0.1000	0.0862	0.0864	0.0826
	Small towns and rural areas	0.2410	0.2735	0.2685	0.2698	0.2419	0.2589
Risaralda	Total	0.1584	0.2561	0.1913	0.1942	0.2111	0.2022
	Municipal seats	0.0442	0.0866	0.0783	0.0904	0.0923	0.0784
	Small towns and rural areas	0.2939	0.4226	0.2995	0.2962	0.3227	0.3270
San Andrés	Total	0.0665	0.1249	0.1016	0.1610	0.1542	0.1216
	Municipal seats	0.0665	0.1249	0.1016	0.1610	0.1542	0.1216
Santander	Total	0.2065	0.2372	0.2218	0.2560	0.2438	0.2330
	Municipal seats	0.0346	0.1085	0.0947	0.1105	0.0918	0.0880
	Small towns and rural areas	0.3896	0.3808	0.3641	0.4082	0.4046	0.3894
Sucre	Total	0.3041	0.3585	0.3739	0.3798	0.3644	0.3561
	Municipal seats	0.1105	0.1520	0.1801	0.1832	0.1647	0.1581
	Small towns and rural areas	0.5281	0.5594	0.5486	0.5612	0.5480	0.5491
Tolima	Total	0.2453	0.2896	0.2370	0.2450	0.2324	0.2498
	Municipal seats	0.0557	0.1130	0.0770	0.0981	0.0935	0.0875
	Small towns and rural areas	0.4522	0.4677	0.3951	0.3777	0.3545	0.4094
Valle del Cauca	Total	0.1325	0.1466	0.1414	0.1649	0.1662	0.1503
	Municipal seats	0.0488	0.0711	0.0650	0.0758	0.0794	0.0680
	Small towns and rural areas	0.2173	0.2397	0.2294	0.2634	0.2547	0.2409
Vaupés	Total	0.5477	0.6418	0.5093	0.5217	0.5364	0.5514
	Municipal seats	0.3040	0.4128	0.3314	0.3266	0.3730	0.3495
	Small towns and rural areas	0.8189	0.8526	0.7079	0.7251	0.7053	0.7620
Vichada	Total	0.4815	0.5466	0.5792	0.6431	0.6030	0.5707
	Municipal seats	0.2951	0.3392	0.3282	0.3707	0.3472	0.3361
	Small towns and rural areas	0.6722	0.7363	0.8830	0.9231	0.8895	0.8208

dimension by year to multidimensional energy poverty at the national level is presented in Fig. 3, using the poverty cut-off line defined as $k = 0.5$, or in other words, defined as sums of deprivations equal to or greater than 50.0 %. Table 6 and Appendix 3 show the contributions of each chosen dimension and variable to the multidimensional poverty index for each year and for each area (municipal seats, small towns and rural areas, and total).

We observe that during the period from 2018 to 2022, the dimension of cooking is the one that has the highest contribution to multidimensional energy poverty of households, both in municipal capitals and small towns and rural areas. The dimension of electricity connection remained as the one that, in proportion, makes the smallest contribution to the MEPI (4.9 % on average per year).

However, at the urban level, the participation of this dimension is much lower (only 1.1 % on average per year), while in rural areas, it is higher (6.3 % on average per year).

Appendix 4 presents the contribution of each selected indicator to the score of multidimensional energy poverty obtained for each department of Colombia and for each of its areas (municipal capitals, small towns and rural areas, and the total). With this information, the energy needs of each territory should be easily identified for the structuring of public policy. For instance, only at the level of the electricity connection dimension, the small towns and rural areas of the departments of Vichada, La Guajira, Guainía, Putumayo, Vaupés, and Guaviare register high deprivation and participation in the MEPI: 21.6 %, 18.7 %, 15.3 %, 11.2 %, 11.0 %, and 10.8 %, respectively. Public policy should be directed especially towards improving access to the electricity grid in these territories. This situation differs for the rural area of the departments of Quindío, Caldas, Santander, and Antioquia, which present a participation of this dimension in a proportion lower than 1.0 %. Likewise, the risk of indoor air pollution after cooking food, due to the lack of suitable cooking space and the necessary implements, presents a high participation in the scores of multidimensional energy poverty for the departments of Sucre (20.7 %), San Andrés (19.7 %), Córdoba (19.5 %), Atlántico (19.4 %), Bolívar (19.4 %), Magdalena (19.2 %), Cesar (18.6 %), and La Guajira (18.2 %). The other dimensions have a relatively equal participation in the MEPI, ranging from 10.0 % to 18.5 %, for all departments and the Capital District, both in urban and rural areas. The dimension of temperature regulation and its indicator should be interpreted with caution for the departments of Boyacá, Cundinamarca, and Nariño, as well as the Capital District, as they encompass mountainous areas with cold thermal floors and cities located at an average altitude exceeding 2000 m above sea level.

For the entire period of study, the departments most affected by energy poverty were La Guajira, Guainía, Vichada, Amazonas, Chocó, Bolívar, and Sucre. The case of Vaupés is particularly interesting as it had the highest score for the years 2018 and 2019, experiencing in 2020 the greatest decrease in the MEPI score that could be observed among the different territories throughout the entire period. On the other hand, the territorial entities with the lowest scores were San Andrés, Bogotá, Valle del Cauca, Quindío, Cundinamarca, and Risaralda. An analysis of the spatial distribution of multidimensional energy poverty in Colombia was carried out using this information (Fig. 4), which is also relevant for the discussion proposed in this paper.

In order to examine the information obtained by the study, the areas observed were put into four groups, according to their average score in the respective quartiles (Fig. 5). The departments that showed a downward trend are Caldas, Casanare, Cundinamarca, and Quindío (Fig. 5a); Tolima, Huila, Boyacá, and Norte de Santander (Fig. 5b); Caquetá, Nariño, Bolívar, Magdalena, and Arauca (Fig. 5c); and Amazonas, and Vaupés (Fig. 5d). Areas that showed an upward trend across the years are San Andrés, Antioquia, Bogotá, Valle del Cauca, Cesar, Santander, Cauca, Sucre, Córdoba, La Guajira, Chocó, Guainía, Guaviare and Vichada (which was the most significant).

As expected, the dispersed rural areas and the other population centres in the departments had lower energy security compared to the municipal capitals (Fig. 6). In fact, within each area, there were significant differences in their average score for each of these study areas (Fig. 7). Urban regions are the main beneficiaries of government energy policies, while energy-poor rural areas do not benefit much and receive only marginal attention in policy implementation. Hence, the poverty gap between urban and rural areas is always higher than 31.0 %, reaching values even higher than 80.0 % in several departments (Table 7). At national level, the existing poverty gap was, on average, 66.13 %. Perhaps this can be explained by access to electricity and clean fuels. Indeed, in the small departmental population centres (secondary towns) more than half of the households did not use modern fuel for cooking (Fig. 8). Moreover, the lack of connection to electricity and natural gas networks in these areas is more than tenfold and double, respectively, compared to that in the departmental municipal capitals. It is particularly interesting that the Capital District, being the second territory with the lowest multidimensional energy poverty score overall and the lowest regarding the municipal seats, exhibits the greatest poverty gap between rural and urban areas during the study period.

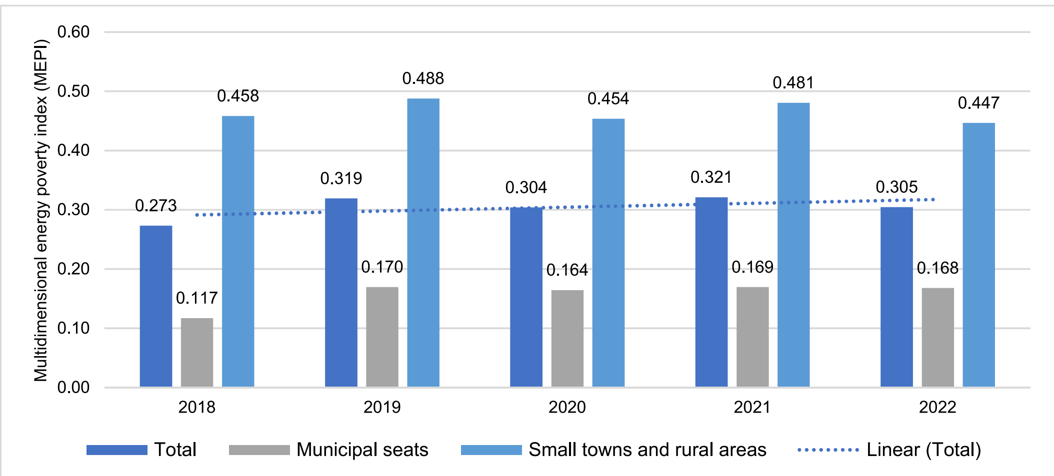

Fig. 1. Multidimensional Energy Poverty Index for Colombia (2018–2022).

Table 4
Decomposition of Multidimensional Energy Poverty Index (2018–2022).

		2018	2019	2020	2021	2022	Mean
Total	Adjusted incidence (MEPI)	0.2731	0.3191	0.3038	0.3212	0.3046	0.3044
	Incidence (*H*)	0.4325	0.5143	0.4914	0.5108	0.4984	0.4895
	Intensity (*A*)	0.6315	0.6204	0.6182	0.6288	0.6113	0.6220
Municipal seats	Adjusted incidence (MEPI)	0.1171	0.1695	0.1643	0.1695	0.1679	0.1577
	Incidence (*H*)	0.2074	0.3027	0.2922	0.3015	0.3007	0.2809
	Intensity (*A*)	0.5646	0.5601	0.5624	0.5621	0.5583	0.5615
Small towns and rural areas	Adjusted incidence (MEPI)	0.4583	0.4878	0.4537	0.4807	0.4466	0.4654
	Incidence (*H*)	0.6995	0.7530	0.7055	0.7308	0.7035	0.7185
	Intensity (*A*)	0.6550	0.6478	0.6431	0.6577	0.6347	0.6477

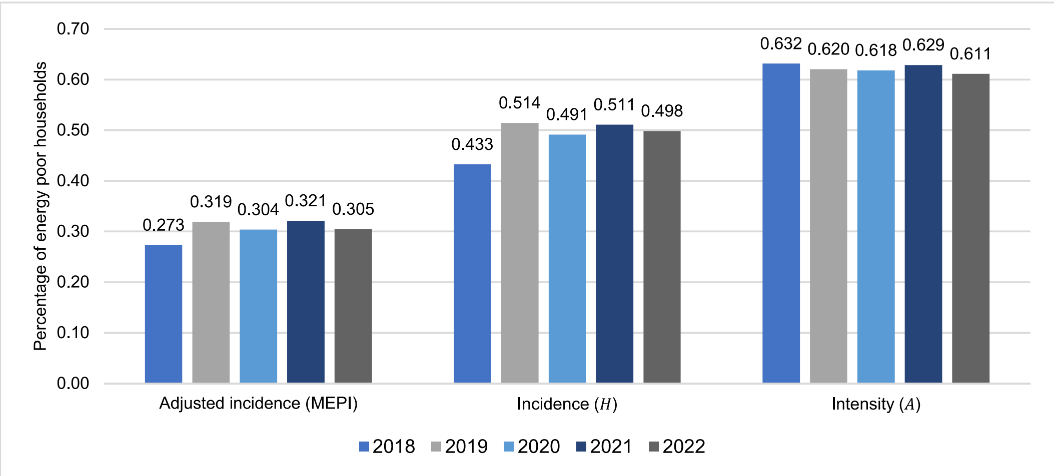

Fig. 2. Multidimensional energy poverty estimates (2018–2022).

6. Discussion

6.1. National analysis

The most affected departments by multidimensional energy poverty share the fact that their population density is low, and they are generally located in off-grid areas, which are mostly departments located in the Orinoco and Amazon regions. In Colombia, electricity supply depends substantially on SIN. It connects generation plants with all national and regional transmission networks and substations, which make up approximately 26,333 km of energy networks. Nonetheless, its coverage is not complete nationwide.

Currently, SIN extends to almost all departments located to the west of the Andes mountains. It starts from the municipality of Cuestecitas in La Guajira and covers a large part of the Caribbean coast (Magdalena, Atlántico, Bolívar, Sucre, Córdoba, and César), down to Antioquia, Norte de Santander, and Santander. It connects the coffee-growing region, Boyacá, Cundinamarca, and Tolima, down to Ecuador, and passes through Valle del Cauca, Cauca, Huila, Nariño, and the municipality of Mocoa (Putumayo). There are even two connection lines to the Orinoco. One runs along the Venezuelan border from the municipality of Toledo (Norte de Santander) to Caño Limón (Arauca) and the other runs from the Chivor substation (Boyacá) to the village of Campo Rubiales (Meta). However, SIN does not cover Vichada, Guainía, part of Casanare, part of Putumayo, Guaviare, Vaupés, Caquetá, and Amazonas. Chocó is an off-grid area; despite being located in the Pacific region in western Colombia. There is a SIN expansion plan for 2034 from the UPME, that aims to reduce the off-grid areas, through the construction of substations in the municipalities of El Carmen de Atrato in southern Chocó and Uribia in northern La Guajira.

As a result of the lack of planning and progress expanding SIN, the Colombian government through the Institute for Energy Solutions (IPSE, Spanish acronym) has taken control of the electricity supply in those regions. Managing public policy in this area presents challenges, depending on the geographic and demographic characteristics of each region. This is particularly the case in the departments of Amazonas and the northern part of Chocó, including the Darién region, areas with a lot of jungle, rivers, and swamps. This is not to say that the other off-grid areas do not have difficult geographic conditions. In fact, in other regions, the energy is broadly generated with oil and other non-clean fuels, which are usually transported by air from the centre of the country. These types of fuels have an environmental cost and improving this situation requires investing greater resources to generate and supply these regions with electricity. That is why the Colombian government is leveraging resources from royalties, from the fund for energy generation in off-grid areas (FAZNI, Spanish acronym) and the fund for social energy (FOES, Spanish acronym).

Table 5
Multidimensional Energy Poverty Index for Colombia by region (2018, 2020 and 2022).

Region	Area	2018			2020			2022		
		MEPI	Incidence (*H*)	Intensity (*A*)	MEPI	Incidence (*H*)	Intensity (*A*)	MEPI	Incidence (*H*)	Intensity (*A*)
Caribbean	Total	0.3097	0.4629	0.6689	0.3417	0.5299	0.6448	0.3392	0.5278	0.6427
	Municipal seats	0.1283	0.2243	0.5720	0.1670	0.2954	0.5654	0.1597	0.2867	0.5571
	Small towns and rural areas	0.5204	0.7401	0.7031	0.5241	0.7748	0.6765	0.5216	0.7727	0.6750
Eastern	Total	0.2293	0.3856	0.5946	0.2402	0.4159	0.5775	0.2346	0.4073	0.5759
	Municipal seats	0.0644	0.1188	0.5420	0.1030	0.1909	0.5397	0.0931	0.1722	0.5406
	Small towns and rural areas	0.3847	0.6370	0.6038	0.3518	0.5991	0.5873	0.3511	0.6010	0.5842
Central	Total	0.2181	0.3682	0.5924	0.2314	0.4025	0.5749	0.2300	0.4031	0.5707
	Municipal seats	0.0785	0.1430	0.5493	0.1070	0.1973	0.5424	0.1093	0.2020	0.5414
	Small towns and rural areas	0.3835	0.6351	0.6039	0.3626	0.6188	0.5859	0.3513	0.6051	0.5805
Pacific	Total	0.3425	0.5573	0.6146	0.3907	0.6536	0.5977	0.3958	0.6633	0.5967
	Municipal seats	0.1676	0.3013	0.5564	0.2457	0.4470	0.5495	0.2514	0.4567	0.5504
	Small towns and rural areas	0.5340	0.8377	0.6375	0.5298	0.8519	0.6220	0.5182	0.8385	0.6181
Bogotá	Total	0.0265	0.0495	0.5350	0.0560	0.1044	0.5361	0.0572	0.1062	0.5388
	Municipal seats	0.0265	0.0495	0.5350	0.0560	0.1044	0.5361	0.0572	0.1062	0.5388
Antioquia	Total	0.2095	0.3657	0.5728	0.2573	0.4611	0.5580	0.2644	0.4725	0.5597
	Municipal seats	0.0796	0.1466	0.5431	0.1430	0.2624	0.5452	0.1401	0.2575	0.5439
	Small towns and rural areas	0.3638	0.6261	0.5810	0.3604	0.6404	0.5627	0.3687	0.6527	0.5649
Valle del Cauca	Total	0.1325	0.2266	0.5850	0.1414	0.2529	0.5590	0.1662	0.2980	0.5579
	Municipal seats	0.0488	0.0889	0.5488	0.0650	0.1195	0.5442	0.0794	0.1464	0.5425
	Small towns and rural areas	0.2173	0.3660	0.5939	0.2294	0.4068	0.5640	0.2547	0.4524	0.5630
San Andrés	Total	0.0665	0.1232	0.5402	0.1016	0.1877	0.5414	0.1542	0.2825	0.5457
	Municipal seats	0.0665	0.1232	0.5402	0.1016	0.1877	0.5414	0.1542	0.2825	0.5457
Amazon-Orinoquia	Total	0.3853	0.5730	0.6725	0.4229	0.6309	0.6704	0.4294	0.6591	0.6515
	Municipal seats	0.2180	0.3757	0.5803	0.2730	0.4669	0.5848	0.2975	0.5162	0.5764
	Small towns and rural areas	0.5850	0.8084	0.7236	0.5954	0.8197	0.7264	0.5803	0.8228	0.7053

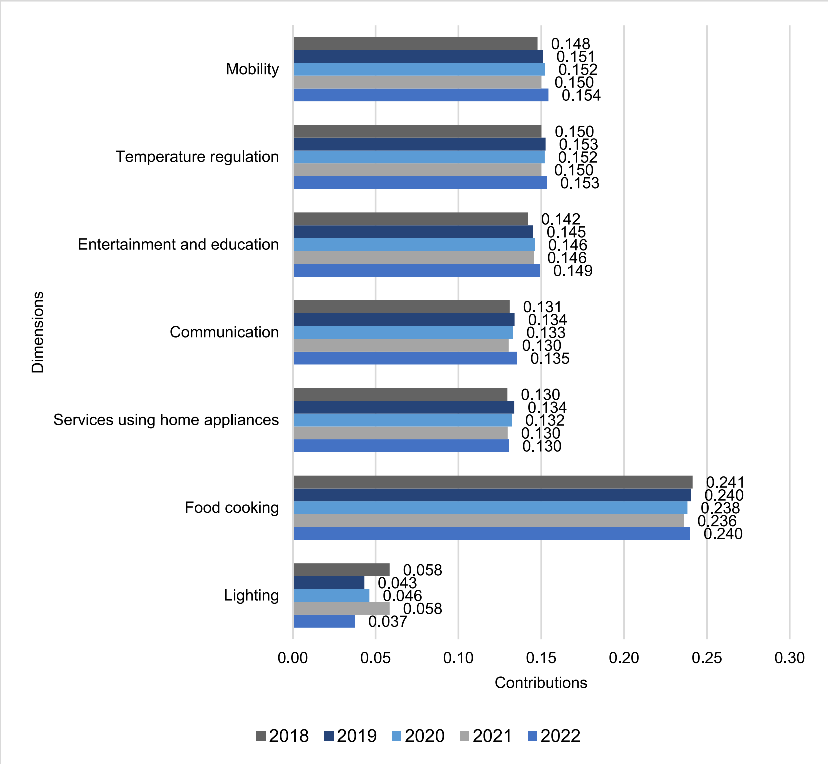

Fig. 3. Contribution of each dimension in multidimensional energy poverty score (2018–2022).

The generation and supply of electricity in off-grid areas is also a big challenge for its allocation through concessions to private operators. In these extensive areas the population is small. For this research, population density (by deciles) was estimated for the 1.123 local areas that comprise the thirty-two departments and the Capital District, using the most recent data from DANE through the 2018 National Population and Housing Census (CNPV, Spanish acronym) (Fig. 9). Showing how the areas with the lowest relative population in the country coincide with the off-grid areas and the highest multidimensional energy poverty values across the period. Areas located in the off-grid areas with low populations densities find it difficult to attract private investment in infrastructure as providing public energy services to these areas is not financially viable for commercial operators. Furthermore, spatial, social, and historical injustices are intimately related to the situation of energy poverty due to inefficient and ineffective institutional decisions. A study by the United Nations Office on Drugs and Crime (UNODC) for Colombia shows that omissions of duty by public institutions and private actors involved in the provision of energy services in off-grid areas are permeated by lack of transparency and abuses of power in the management of public resources [144]. As a matter of fact, the probability of corruption in off-grid areas increases compared to the National Interconnected System (SIN), as they are marginalized due to geographical isolation, insecurity, and inequity [145].

Given the difficulties outlined above, it is likely that the cost of the electricity will be higher for users living in off-grid areas than in SIN areas. However, people living in the off-grid areas tend to have lower incomes, which is why the government subsidizes users through the Solidarity Fund for Subsidies and Income Redistribution (FSSRI, Spanish acronym). In fact, since the 1990s, a fare policy has been in operation nationwide in SIN and off-grid areas, in which users are classified according to social stratification that considers both solidarity and contribution criteria. Under this system, the user can then assume a role as a contributor or subsidized individual using cross-subsidies (Law 188 of 1995 and Resolution 114 of 1996 of the CREG). The system sets a limit for subsistence consumption per household for the electric energy service. In 1995, subsistence consumption was equal to 200 kWh/month. At present, it is 173 kWh/month for users living less than 1000 m above sea level and 130 kWh/month for those located above 1000 m. Taxpayers must pay an additional 20 % towards their actual electricity consumption, which pays for the subsistence electricity consumption for a subsidized user (Table 8). The users in strata 1, 2 and 3 must pay the whole cost of any additional consumption.

After more than twenty years of the cross-subsidy system and despite constant criticism of its inefficiency in terms of social mobility [146], no impact assessment of the tariff policy has been carried out to date. In fact, households located in rural areas and small population centres are usually categorized in low social strata. However, as indicated above, there is a real poverty gap in all the areas studied in these departments and their capitals (Figs. 6 and 7, Table 7). The results obtained in this research should motivate the planning of specific public policy by territories that allows for alleviating existing gaps and factors that drive energy poverty.

Indeed, there must be legal and institutional coordination of macroeconomic policies in planning outlined in the short-term National Development Plans (PND) and the projection of the mining-energy sector in the long term contained in the National Energy Plan (PEN) with a horizon to 2050 [18]. The PND 2022–2026 is aligned with SDG7 and contemplates productive transformation,

Table 6
Contribution of lighting and food cooking dimensions in multidimensional energy poverty score (2018–2022).

Year	Area	Lighting		Food cooking					
		Access to electricity and lighting from the public energy service	Subtotal	Type of fuel for cooking	Access to natural gas service connected to the public network	Modern kitchen in the home	Has an electric or gas stove	Has an electric or gas oven	Subtotal
2018	Total	0.058	0.058	0.038	0.048	0.026	0.035	0.095	0.241
	Municipal seats	0.014	0.014	0.011	0.044	0.041	0.016	0.106	0.217
	Small towns and rural areas	0.072	0.072	0.046	0.049	0.022	0.04	0.091	0.249
2019	Total	0.043	0.043	0.032	0.045	0.025	0.030	0.107	0.240
	Municipal seats	0.008	0.008	0.008	0.039	0.031	0.013	0.119	0.211
	Small towns and rural areas	0.057	0.057	0.042	0.048	0.023	0.037	0.103	0.252
2020	Total	0.046	0.046	0.032	0.045	0.026	0.030	0.105	0.238
	Municipal seats	0.012	0.012	0.009	0.04	0.035	0.014	0.116	0.214
	Small towns and rural areas	0.059	0.059	0.041	0.047	0.022	0.036	0.101	0.248
2021	Total	0.058	0.058	0.031	0.044	0.026	0.029	0.105	0.236
	Municipal seats	0.012	0.012	0.009	0.039	0.035	0.014	0.118	0.214
	Small towns and rural areas	0.076	0.076	0.04	0.046	0.023	0.035	0.101	0.244
2022	Total	0.037	0.037	0.032	0.044	0.027	0.030	0.107	0.240
	Municipal seats	0.009	0.009	0.007	0.038	0.036	0.014	0.117	0.212
	Small towns and rural areas	0.049	0.049	0.041	0.047	0.024	0.036	0.103	0.251

internationalization, and action for climate, as well as the strategic action of a fair, safe, reliable, and efficient energy transition. It aims to balance social justice with respect for nature, striving for the closure of energy gaps through the universalization of service [38]. However, as mentioned earlier, this plan still lacks projections of public policy and legal and financial decisions to effectively reduce energy poverty.

On the other hand, the PEN has, among its objectives, energy as the axis of economic and social development, as well as ensuring the coverage of energy services with inclusivity and territorial development, objectives associated with improving the quality of life. Nevertheless, it does not have a diagnosis of the conditions of energy poverty in households. The indicative plans for expanding the electricity grid are based on estimates of the electricity coverage index, as illustrated in Section 2 of this paper. However, such unidimensional and quantitative estimation is insufficient to determine the range of problems associated with household energy uses. In fact, this index is biased because it does not identify whether the household is connected to the National Interconnected System (SIN) or to a specific local distribution system in an off-grid area, nor the economic and non-economic costs of that service provision. Additionally, the planning of the energy sector is indicative and not mandatory for economic agents involved, such as network operators and energy marketers. Therefore, infrastructure planning in low-market interest territories, such as La Guajira, Chocó, Vichada, and Amazonas, is hardly executed. On the contrary, in territories like Valle del Cauca and Antioquia, infrastructure construction is constant and the quality indicators in the provision of the service are considerably higher.

In summary, as highlighted, centralized planning of the sector in the medium term includes policies related to energy poverty, although they do not address it or define it explicitly to recognize sector-specific energy needs. Only the national rural electrification plan, which is under discussion, aims to characterize the socioeconomic situation of vulnerable households and demand behaviour, as illustrated in its working documents. This is expected to project resources and financing mechanisms for projects with public-private participation that make universalization of service viable, as well as offering technical assistance and training for renewable energy generation projects. This research can enrich specific public policy efforts in this regard. In fact, it was only in 2022 that the national plan for the substitution of firewood and other highly polluting fuels was designed for the first time, given the increase in the use of these fuels following the COVID-19 pandemic [139]. According to our results (Appendix 4), the rural areas of the departments of Boyacá, Córdoba, Sucre, Huila, Santander, Norte de Santander, Vaupés, and Amazonas present a higher participation of the lack of clean cooking in the MEPI. At the urban level, these departments are Vaupés, Guainía, Vichada, Amazonas, Chocó, Nariño, and San Andrés. The public policy for fuel substitution should follow these estimations for the identification of energy needs. Special attention should be paid to the financial difficulties inherent in these types of policies since it is possible that a household has access to electricity and natural gas services but may not be able to afford their use for cooking.

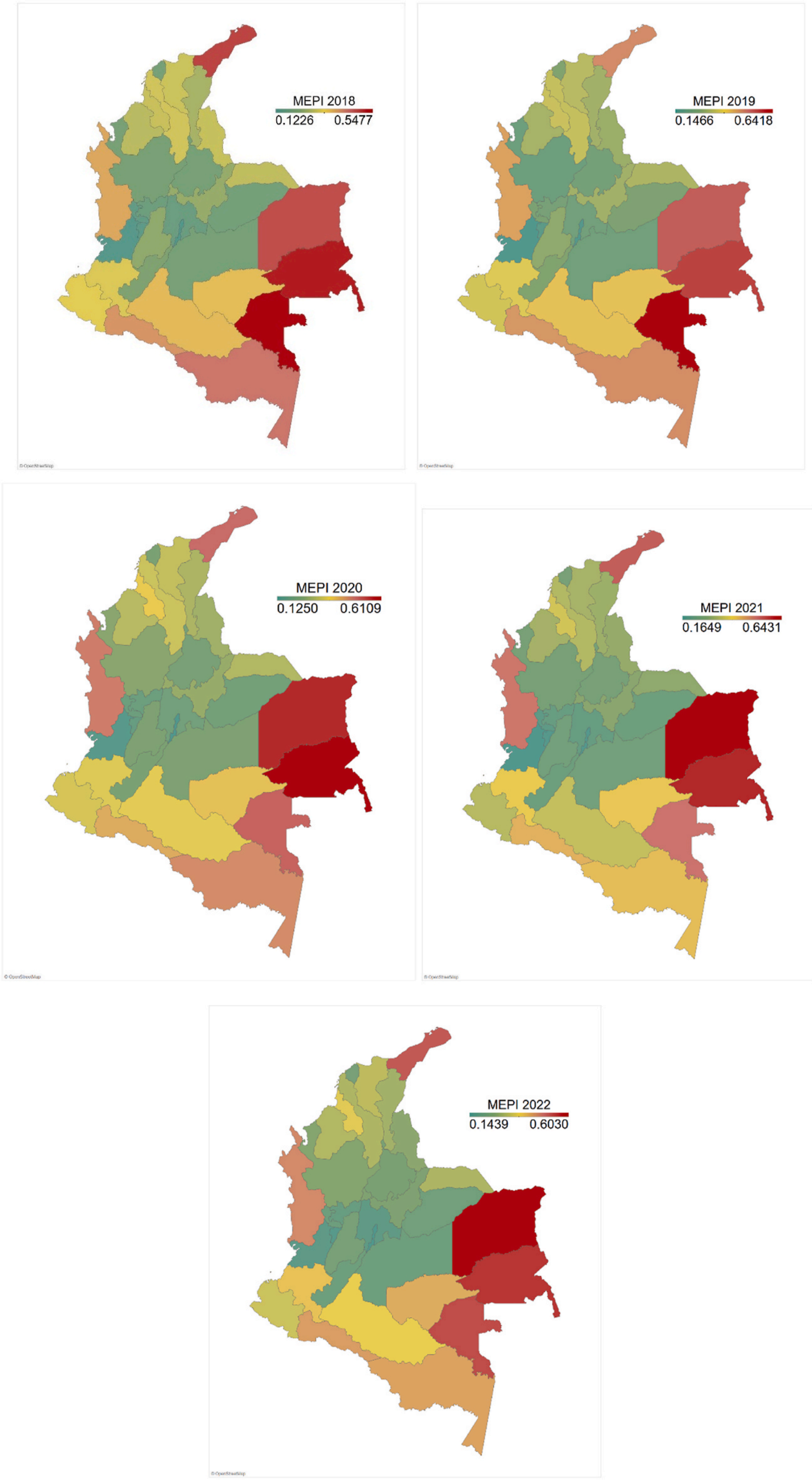

Fig. 4. Distribution of multidimensional energy poverty in Colombia (2018–2022).

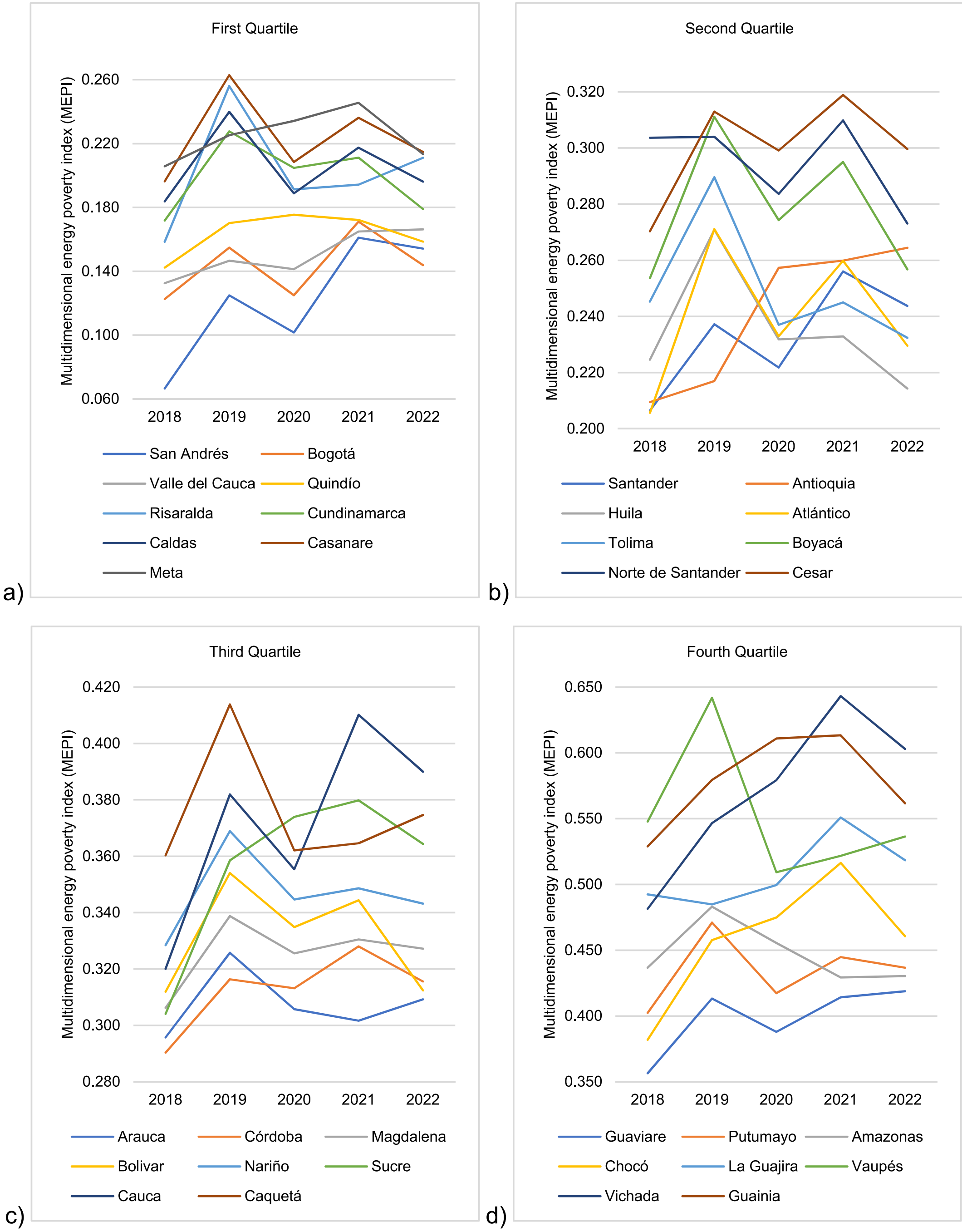

Fig. 5. Behaviour of the Multidimensional Energy Poverty Index by department (2018–2022).

6.2. Departmental analysis

In addition to the previous examination of the national situation, this study also includes a local analysis for some of the regions that have specific characteristics. The department of La Guajira, for example, has the highest energy poverty for the entire country for the period. This coincides with the financial poverty (estimated by DANE), which was the highest in the country in 2020 and 2021 (66.3 % and 67.4 %, respectively). Paradoxically, it has the largest open-pit coal mine in the world (69,000 ha) that produced a total of 23.4 million tons in 2021 [147]. However, the region's MEPI score remained the same with one of the highest gaps between small population centres and the main cities. This clearly demonstrates that the benefits associated with economic and social growth are not passed down to this department's population, especially in its most remote areas in the north of the department. Two factors that explain the high degree of energy poverty in La Guajira are the fact that most of its remote off-grid areas (where most of its indigenous

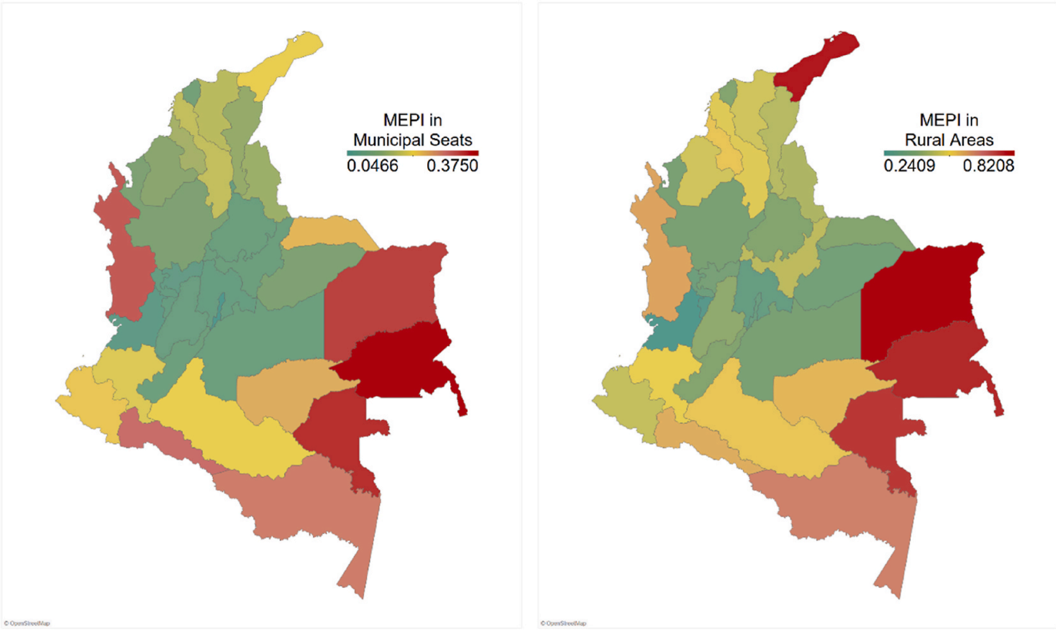

Fig. 6. Average distribution of multidimensional energy poverty in municipal seats (urban areas) and rural areas (2018–2022).

Wayú population live). The second is the fact that its ecosystem is composed of desert, tropical dry forest, and arid steppe, which has historically made agriculture unviable. Although La Guajira showed increasing energy poverty in the period, this is expected to decrease due to its 15,000 MW wind potential (equivalent to 50 % of Colombia's wind potential). However, this situation has spurred the start of new works, such as the HVDC - Alta Guajira transmission line, that is predicted to bring a constant electricity supply to the region [16]. Furthermore, an increase in the number of electricity generation projects is expected, especially photovoltaic and wind projects. These are likely to increase requests for connections to SIN, which will activate the public policy to assign transmission capacity to generators, according to Resolution 40311 of 2020 of the Ministry of Mines and Energy.

Vaupés, Vichada and Guainía had substantially high energy poverty during the years studied. The Venezuelan energy crisis played an important role in their case. The Venezuelan company CADAFE was the main energy supplier to these regions, because of an agreement between Colombia and Venezuela. It was cheaper for Colombia to make that agreement rather than to extend SIN to the

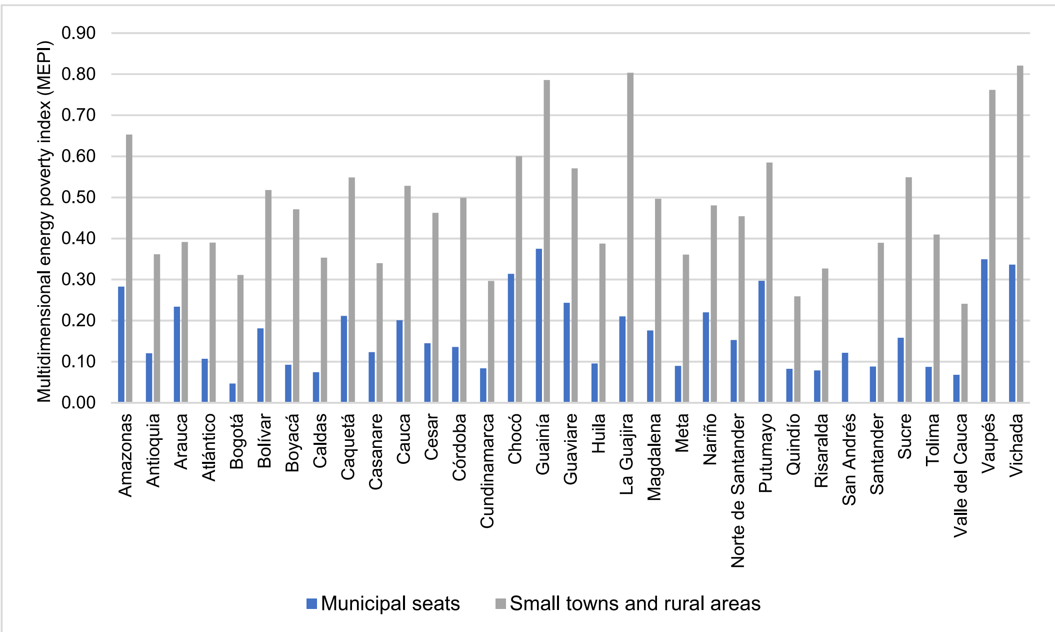

Fig. 7. Average Multidimensional Energy Poverty Index for Colombia in urban and rural areas (2018–2022).

Table 7
Rural-urban poverty gab.

Department	2018	2019	2020	2021	2022	Mean
National	74.45%	65.24%	63.78%	64.74%	62.41%	66.13%
Amazonas	65.47%	53.13%	54.93%	62.10%	46.82%	56.49%
Antioquia	78.11%	68.88%	60.31%	64.58%	62.00%	66.78%
Arauca	45.45%	40.31%	41.92%	41.77%	31.31%	40.15%
Atlántico	80.03%	71.34%	70.67%	68.99%	72.30%	72.67%
Bogotá	90.13%	90.56%	75.52%	84.96%	80.58%	84.35%
Bolivar	71.69%	61.77%	57.94%	66.89%	66.60%	64.98%
Boyacá	87.97%	70.92%	80.61%	80.49%	82.46%	80.49%
Caldas	86.35%	69.20%	76.66%	83.57%	79.52%	79.06%
Caquetá	66.15%	57.68%	55.86%	68.74%	58.17%	61.32%
Casanare	73.89%	67.55%	66.51%	55.15%	54.75%	63.57%
Cauca	75.09%	51.62%	60.76%	60.84%	61.31%	61.93%
Cesar	78.74%	70.12%	66.42%	63.81%	63.38%	68.49%
Córdoba	73.36%	74.26%	73.76%	74.58%	67.20%	72.63%
Cundinamarca	87.03%	62.99%	67.18%	71.21%	69.84%	71.65%
Chocó	65.36%	44.16%	50.15%	40.97%	38.39%	47.80%
Guainía	55.48%	52.38%	51.80%	51.09%	50.84%	52.32%
Guaviare	74.64%	60.67%	53.36%	53.66%	42.64%	56.99%
Huila	82.32%	74.44%	74.11%	75.27%	69.34%	75.10%
La Guajira	74.24%	72.36%	74.04%	72.72%	75.99%	73.87%
Magdalena	71.56%	65.65%	61.32%	63.53%	60.44%	64.50%
Meta	81.38%	75.21%	78.10%	69.48%	71.54%	75.14%
Nariño	65.06%	50.48%	49.82%	51.11%	54.16%	54.13%
Norte de Santander	73.52%	64.79%	62.77%	61.22%	69.12%	66.28%
Putumayo	57.40%	41.70%	47.52%	54.31%	44.73%	49.13%
Quindío	76.19%	69.59%	62.74%	68.04%	64.28%	68.17%
Risaralda	84.96%	79.50%	73.87%	69.50%	71.39%	75.84%
Santander	91.12%	71.50%	74.00%	72.92%	77.31%	77.37%
Sucre	79.07%	72.82%	67.17%	67.36%	69.94%	71.27%
Tolima	87.68%	75.85%	80.50%	74.03%	73.61%	78.33%
Valle del Cauca	77.56%	70.31%	71.65%	71.23%	68.82%	71.91%
Vaupés	62.88%	51.58%	53.19%	54.96%	47.12%	53.95%
Vichada	56.09%	53.94%	62.83%	59.84%	60.97%	58.73%

municipalities in Vaupés, Vichada and Guainía. However, due to the high rate of inflation in Venezuela, the company increased its fares by 2000 % from 2018 [148], which made the service unfeasible. In view of this situation and with the objective of reducing dependence on Venezuela in that region, a new company (Refoenergy Bita) started operating in 2021 with a forest biomass electricity generation plant with a capacity of 4.5 MWh. In addition, in 2014, construction of an electrical interconnection line was started to extend SIN to Casanare and Vichada. The project cost $17.8 million dollars and started operating in 2023.

The MEPI results for the department of Chocó are interesting because, although it is geographically close to SIN, a large part of its area is an off-grid area (approximately 48,000 users), and the electric energy service coverage is the lowest of the four departments in

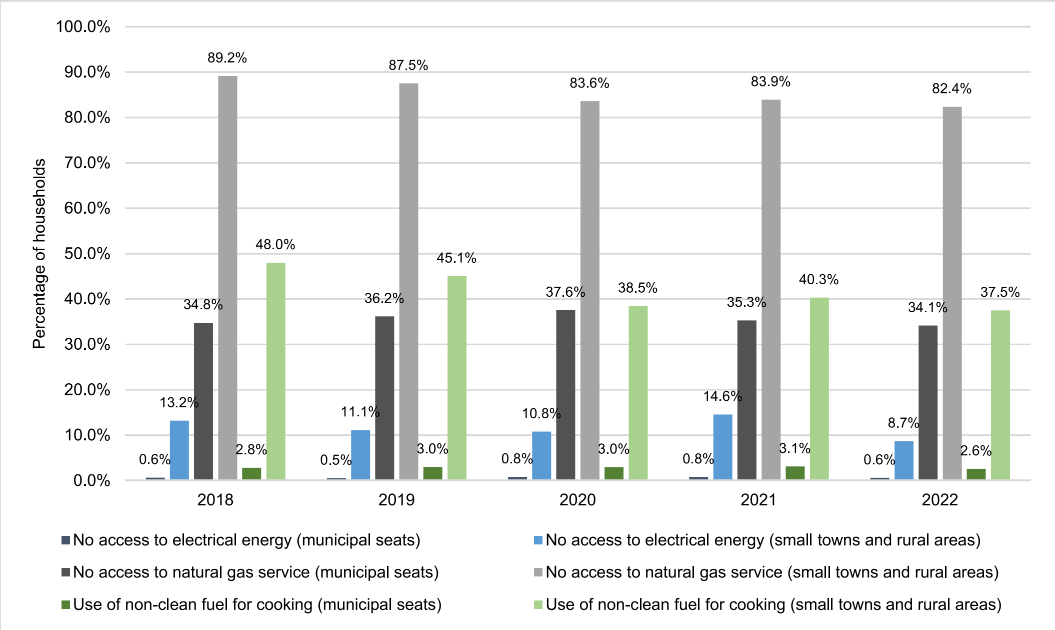

Fig. 8. Percentage of households without access to electricity, natural gas service or clean cooking fuels (2018–2022).

the Pacific region. Like La Guajira, the energy poverty estimated in this study for Chocó coincides with financial poverty (estimated by DANE), which was the second worst in the country in 2020 and 2021 (64.5 % and 63.4 %, respectively). Despite the plans projected for the coming years, there are no large power generation plants or gas exploration points in this department. In the 2012 expansion plan, it was estimated that an investment of approximately $100.000 dollars was needed to connect a large part of the southern part of the department to SIN, but to date that has not happened. Chocó is not well represented in SIN expansion agenda, and it is not certain whether the projected work in the municipality of El Carmen de Atrato will happen.

Sucre and Bolívar (in the Caribbean region) are in the same situation as Chocó. They are located to the west of the Andes, but their MEPI score is higher than the national average. However, their situation cannot be explained by the presence of the off-grid areas. In fact, Bolivar has thermal generation and transmission substations. Although Sucre is connected to SIN, there is a lack of supply, caused by the depletion of transformation capacity, low voltages, and overloads [17]. In Bolivar the situation is the same in terms of the

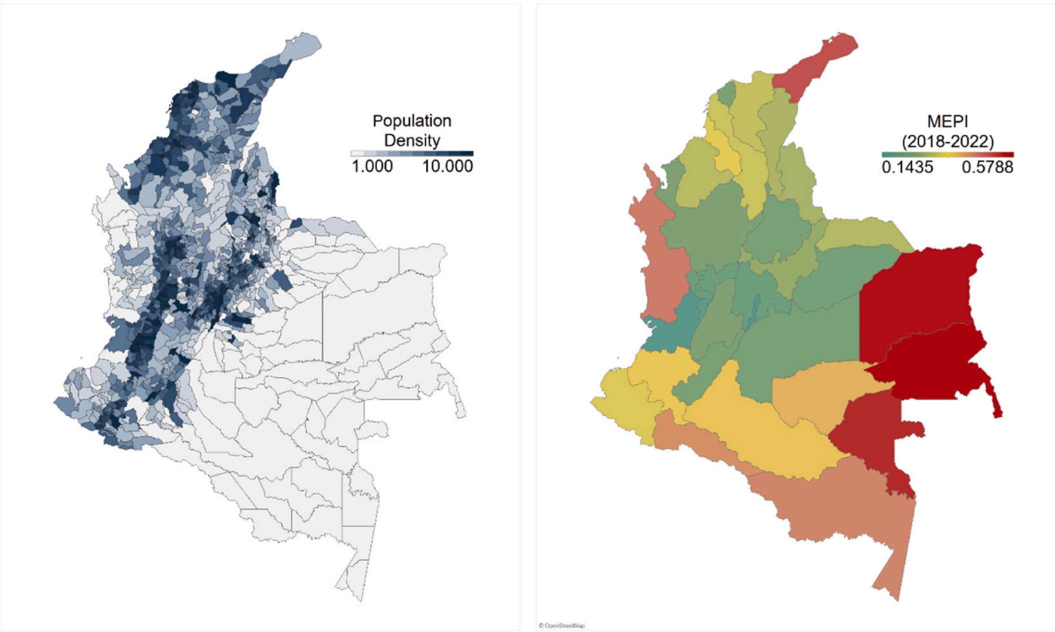

Fig. 9. Population density by deciles in Colombia (2018) and its comparison with the average MEPI (2018–2022).

Table 8
Socioeconomic stratification system for energy services in Colombia.

Socioeconomic stratification	Electrical energy
Strata 1	30 % subsidies
Strata 2	20 % subsidies
Strata 3	15 % subsidies
Strata 4	0 %
Strata 5	20 % contribution
Strata 6	20 % contribution

distribution network, but its energy poverty decreased in the years studied. The energy problems in the country's Caribbean region have multiple causes. These include the lack of modernization and investment in infrastructure, commercial monopolies, and the poor quality of service offered by distribution and commercialization companies [149].

The decreasing trend in the department of Vaupés can be explained by the energy projects implemented during the study years (2018–2022), that's generation capacity reached 2010 kWp. These projects allowed the installation of 2866 individual photovoltaic systems and among the beneficiaries are 130 indigenous territories. The work cost $12.5 million dollars and was funded by FAZNI and the General Royalties System. However, at present, the department still presents a relatively high MEPI score compared to other territorial entities in the country.

The departments with the lowest energy poverty share the fact that they belong to SIN, even though their geographic conditions and productive systems are different. From a review of the generation and transmission expansion plans, it is evident that the projects recommended in the indicative planning should be executed as soon as possible. For instance, in Valle del Cauca in 2010 construction began on the 230/115 kW Alférez substation (with the latest generation of encapsulated technology in an area of 4000 m2). By 2014 it was already operating and connected to SIN. The same occurred with the reconfiguration of 1.4 km of the Yumbo - San Berdardino 230 kW line. In Antioquia, the Hidroituango hydropower plant (with an installed generation capacity of 600 MW) has now been operating commercially since 2022. A second phase, adding another 1200 MW, is planned to start operation between 2023 and 2035. These projects guarantee the supply of electricity to meet the demand in SIN, and strengthen the national transmission system, which allows the connection of potential new industrial users.

7. Conclusion and policy implications

The intertemporal assessment of energy poverty is crucial for designing adequate public policies [150,151]. As recognized by Gouveia et al. [152] and Bezerra et al. [69], studies on energy poverty in countries with vast territorial expanses require comprehensive characterizations to identify sector-specific needs. While Colombia is not as significantly large as Russia, Brazil, Canada, China, or the United States of America, it still ranks 25th in size. Particularly, it boasts diverse ecosystems, sociodemographic conditions, thermal floors, and climates. It is reasonable to assume that any analysis of energy poverty must account for the heterogeneous conditions across the country.

In this paper, a MEPI was designed according to the information provided by the ECV household survey of the DANE. The MEPI reviewed the country's thirty-two departments and the Capital District. It used nested weighting, which grants a subjective weight to the dimensions within the study and an entropy method was used for each of the variables. This MEPI differs from past research, which used a MEPI that was limited and only provided an estimation for the statistical regions defined by DANE (which may introduce bias). Furthermore, previous research in Colombia did not include all the variables in this study (such as: household appliances, telephone landline, TV service, and entertainment devices), or dimensions (such as temperature regulation and mobility), that have already been reviewed by the literature [80,86,153]. This research aims to provide a broader definition of energy poverty, covering various dimensions of energy system and resource use, through a quantitative approach to deprivation. By achieving this, it is sought to address the institutional and legal deficiency of the country, which has not yet characterized the concept of energy poverty for the formulation of specific public policy. Our approach aims to provide a deeper understanding of energetically vulnerable households, by not limiting itself to mere coverage considerations.

The results indicate that energy poverty in Colombia did not improve between 2018 and 2022; instead, it slightly increased. As expected, the off-grid areas are in a more serious situation regarding energy than municipalities located in SIN. As long as this inequality of access to energy supply services persists, the situation will remain unchanged. Unquestionably, the results suggest that there are significant differences between the departments studied in this paper, and between their main cities and the other population centres. The latter have a higher energy poverty in all the departments. More research could be conducted on the Capital District to review the causes of its large energy poverty gap within its component areas. La Guajira should be evaluated after new interconnection works proposed by the UPME in the coming years, as their implications could be significant for its small population centres and its rural areas. In general, eastern areas of Colombia have a higher MEPI than their counterparts in the west. However, La Guajira, Chocó, Sucre, and Cauca, located on the western side of the Andes, also suffer chronic energy poverty.

In addition to quantifying energy poverty for each of the country's departments and the Capital District, in both rural and urban areas, this research aims to draw attention to the fundamental need for identifying household energy needs at the local level. With this, the following key findings can be explored for the design of public policies aimed at eradicating energy poverty in Colombia.

First, as recognized by Meyer et al. [154], Oswald et al. [155], and Ye & Koch [74], it is necessary to understand the determinants of energy poverty to design more effective policy initiatives. Therefore, we suggest the government's need to identify comprehensive, sector-specific, and specific metrics of energy poverty that allow for the characterization of the energy needs of the population that will benefit from public policy. This study has demonstrated that the use of the Electricity Coverage Index (ICEE, Spanish acronym) calculated by the UPME [7] for the formulation of public policy aimed at reducing energy gaps is not sufficient. In terms of affordability, mere connection to the electrical system does not guarantee a true well-being. As identified in Table 6, Appendix 3 and Appendix 4, energy poverty can manifest in multiple ways. Particularly, the inability to acquire new efficient appliances or pay the bill for utilities existing in the household may lead to inadequate consequences for vulnerable individuals. For example, it may lead them to use non-clean fuels for cooking, lack adequate means for education and their development of human capital, or ensure their thermal comfort. Therefore, the institutional definition of energy poverty poses a simultaneous obligation and necessity for state actors. Especially for the implementation of the recent national plan for the substitution of firewood and other highly polluting fuels [139].

Second, a reassessment of government programs and plans in the medium and long term is required. In particular, the review and articulation of the PEN, whose horizon projected by UPME is set for the year 2050, and its expansion plans along with the short PND. Legal and financial decisions are needed to effectively reduce energy poverty. However, we estimate that the indicative national policy is not sufficient to achieve effective expansion of electrical coverage or connection of more households to SIN. Given that Colombia's political organization model is political centralization and administrative decentralization, with the expectation of greater transfer of competencies to achieve specific goals in the provision of utilities [156]; guidelines and criteria are needed to enable the distribution of public services and social infrastructure balanced across departments. We assume that a more participatory involvement of local administrations in energy decision-making may be appropriate to define new paths of social welfare in the most remote and difficult-to-connect territories to SIN. However, we recognize that further research is needed to explore the advantages of local governance for managing energy resources as alternatives to excessive political centralization. So far, there are only studies that reveal the benefits of coordinating different levels of territorial government for land management [157], for collaborative governance [158], and for addressing climate change [159]. The fact is that there is a relative overestimation of the positive impact of political centralization during energy decision-making to reduce poverty. In environmental matters, on the contrary, there are local measures related to climate change and sustainable development [160], and there is empirical evidence of the benefits of environmental decentralization to reduce carbon emissions [159,161]. The lack of technical knowledge of departmental and municipal governments about energy gaps and their implications hinders the implementation of sectoral public policies and strategic actions. Perhaps a local management approach could be an interesting element to consider for the formulation and implementation of the national rural electrification plan.

Third, and related to the previous aspect, this study demonstrates a possible underlying relationship between the presence of energy poverty and the location of a household in off-grid areas. That is, the fact that a household located in off-grid areas does not necessarily mean lack of access to public energy service, given local alternatives. But, as mentioned earlier, the presence of a household in off-grid areas increases its probability of being in a multidimensional energy poverty situation, especially if it is in a rural area. Thus, the results obtained should be subject to review by decision-makers, who should assess the favourable or unfavourable impacts of SIN expansion indicative plans, as well as local connection alternatives developed in the most remote territories. For example, the results regarding the department of Vaupés (off-grid area) show a significant decrease in energy poverty with the occurrence of individual and focused projects in small territories. Although its significant score persists in the studied time, it can guide new public policies in other territories. Even for households located in off-grid areas, electric connection projects prioritizing medium-scale generation and the use of renewable energies could be formulated. This could be the basis for improving the quality of life in the most remote areas of the territory or those whose connectivity is a real challenge due to existing geographical conditions.

Whilst the results obtained through the MEPI may be limited by the choice of dimensions and their weighting [20,22,162], as the main objective of this research was to make a first approach to the formal measurement of energy poverty in Colombia through a replicable index over time (using data provided by the ECV or any other survey for the coming years), we decided to include the greatest possible number of variables, dimensions, and indicators that could be extracted from databases and previously used by the literature [162]. Future studies may seek to measure energy poverty from other perspectives, perhaps a bit more quantitative and pecuniary, as done by Cabello Eras et al. [27]. Naturally, we should not overlook the need to evaluate the public tariff policy in the country and its historical effects; the affordability of clean fuels for people in rural areas (since access to the electricity or natural gas grid may not be sufficient to cook with clean fuels, given the lack of appliances that facilitate efficient energy use or the household's inability to pay for such use); the evolution of utilities prices in off-grid areas compared to households located in SIN, and their impact on expenditure; among other alternatives.

Although the national database is not very detailed in the variables questioned for the quality of electrical service and energy uses, advances in the methodological design of the questionnaires by DANE can favor these studies. For this, it is crucial that authorities focus their attention on defining energy poverty and encouraging the application of various methodologies to measure it, assess its causes, and possible solution alternatives. This will be input for obtaining better data soon. Thus, despite the methodological limitations of MEPI, our research yields important results for Colombia and its territorial entities. With careful adjustment at the local level, this study can be replicated by other Latin American countries and those in development.

In fact, in the international scenario, the methodology proposed for this study can be used to analyse energy poverty in countries with similar climatic and natural conditions to Colombia. That is in tropical and equatorial countries where dependence on hydroelectricity is high, and the vulnerability of the energy system to climate change is higher. Assessing multidimensional energy poverty in a broad and detailed way will allow national and regional public policies to necessarily relate energy issues to social mobility and well-being, especially health and security. The dimensions and variables selected in this article should then be replicated in these new studies, with the limitations specific to each territory.

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Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Claudia Lorena Esquivel García: Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Guillermo León Toro-García:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Guillermo Leon Toro-Garcia reports financial support was provided by Department of Chocó (Colombia), General Participation System, Researchers and Innovators Program (BPIN 2022000100068).

Appendix 1. Dimensions and variables employed by the scientific articles

Dimension	Ref.	Variable	Ref.
Lighting	[20,63,11,24,65,66,69,70,72,73,75,76,78–82,84–86,89,153]	Access to electricity and lighting from the public energy service	[20,63,11,24,65,69,70,72,73,76,78,80–82,84–88]
Cooking	[20,63,11,24,65,66,69,70,72,73,75,76,78–82,84–86,89,153]	Type of fuel for cooking	[20,63,11,24,65,69,70,72,73,76,78–81,84–89,103]
		Access to natural gas service connected to the public network	[78,82,87]
		Modern kitchen in the home	[20,63,11,24,65,72,84,86]
		Has an electric or gas stove	[79,81,82]
Services using home appliances	[20,63,24,65,66,70,72,73,75,76,80,81,84–86,89]	Has a washing machine	[11,24,80,103]
		Has a refrigerator	[20,63,11,24,65,69,70,72,73,76,78,80,81,84–89,103]
		Has an iron	[80]
		Has a microwave	[11]
Communication	[20,63,24,65,66,70,72,76,80,81,84–86,89]	Has a cellphone	[11,24,65,70,72,76,80,81,84–86,88]
		Has a landline	[20,63,65,70,72,80,81,85,86,88]
		Has a desktop computer or laptop	[11,24,80,84,86–88,103]
		Has a tablet	[84,103]
		Has internet	[11,24,69,80,84]
Entertainment and education	[20,63,24,65,66,72,73,76,80,81,84–86,89]	Has a TV or radio	[20,63,11,24,65,69,70,72,73,76,80,81,84–87,89,103]
Temperature regulation	[80,86]	Has air-conditioning or a fan	[11,69,80,84,88,89,103]
		Has a water heater	[89]
Mobility	[80,153]	Has a car	[80,103]
		Has a motorbike	[80]

Appendix 2. Estimations of the weights of variable (w_j) for the year 2018

Dimension	Variable	Sample	Frequency of possession	Probability of possession	Probability of non-possession	Entropy value (e_j)	Variation coefficient (d_j)	Weights of dimensions (α_n)	Weights of variable (w_j)
Lighting	Access to electricity and lighting from the public energy service	86577	81049	0.9361	0.0639	0.2374	0.7626	0.2500	0.2500
Food cooking	Type of fuel for cooking	86577	66230	0.7650	0.2350	0.5453	0.4547	0.2500	0.0460

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Dimension	Variable	Sample	Frequency of possession	Probability of possession	Probability of non-possession	Entropy value (e_j)	Variation coefficient (d_j)	Weights of dimensions (α_n)	Weights of variable (w_j)
	Access to natural gas service connected to the public network	86577	34926	0.4034	0.5966	0.6744	0.3256	0.2500	0.0329
	Modern kitchen in the home	86577	73273	0.8463	0.1537	0.4290	0.5710	0.2500	0.0578
	Has an electric or gas stove	86577	70848	0.8183	0.1817	0.4739	0.5261	0.2500	0.0532
	Has an electric or gas oven	86577	12188	0.1408	0.8592	0.4064	0.5936	0.2500	0.0601
Services using home appliances	Has a washing machine	86577	42938	0.4960	0.5040	0.6931	0.3069	0.1000	0.0178
	Has a refrigerator	86577	65502	0.7566	0.2434	0.5550	0.4450	0.1000	0.0258
	Has an iron	86577	39842	0.4602	0.5398	0.6900	0.3100	0.1000	0.0180
	Has a microwave	86577	9226	0.1066	0.8934	0.3393	0.6607	0.1000	0.0384
Communication	Someone in the home owns a cellphone	86577	79016	0.9127	0.0873	0.2963	0.7037	0.1000	0.0195
	Has a landline	86577	11043	0.1276	0.8724	0.3817	0.6183	0.1000	0.0171
	Has a desktop computer	86577	10060	0.1162	0.8838	0.3593	0.6407	0.1000	0.0177
	Has a laptop	86577	16404	0.1895	0.8105	0.4855	0.5145	0.1000	0.0143
	Has a tablet	86577	5014	0.0579	0.9421	0.2212	0.7788	0.1000	0.0216
	Has internet	86577	30044	0.3470	0.6530	0.6456	0.3544	0.1000	0.0098
Entertainment and education	Has a conventional color TV	86577	43154	0.4984	0.5016	0.6931	0.3069	0.1000	0.0087
	Has an LCD, plasma, or LED TV	86577	35962	0.4154	0.5846	0.6788	0.3212	0.1000	0.0091
	Has a cable or satellite TV subscription	86577	46474	0.5368	0.4632	0.6904	0.3096	0.1000	0.0088
	Has a video player (DVD, blue ray, etc.)	86577	13772	0.1591	0.8409	0.4381	0.5619	0.1000	0.0159
	Has an audio player	86577	32799	0.3788	0.6212	0.6635	0.3365	0.1000	0.0095
	Has a digital music, video, and image player (mp3, mp4, iPod)	86577	2990	0.0345	0.9655	0.1502	0.8498	0.1000	0.0241
	Has a video game console (Play Station. X-BOX. Wii. PSP. Nintendo. Gameboy. etc.)	86577	3165	0.0366	0.9634	0.1568	0.8432	0.1000	0.0239
Temperature regulation	Has air-conditioning	86577	4027	0.0465	0.9535	0.1881	0.8119	0.1000	0.0452
	Has an electric fan or handheld fan	86577	37247	0.4302	0.5698	0.6834	0.3166	0.1000	0.0176
	Has an electric or gas water heater	86577	8920	0.1030	0.8970	0.3317	0.6683	0.1000	0.0372
Mobility	Has a car	86577	9274	0.1071	0.8929	0.3404	0.6596	0.1000	0.0636
	Has a motorbike	86577	27291	0.3152	0.6848	0.6232	0.3768	0.1000	0.0364

Appendix 3. Complement to Table 6: Contribution of each dimension and variable in multidimensional energy poverty score (2018–2022)

Dimension | Variables	2018			2019			2020			2021			2022		
	Total	M.S.	R.A.	Total	M.S.	R.A.	Total	M.S.	R.A.	Total	M.S.	R.A.	Total	M.S.	R.A.
Services using home appliances	**0.130**	**0.140**	**0.127**	**0.134**	**0.143**	**0.130**	**0.132**	**0.141**	**0.129**	**0.130**	**0.140**	**0.126**	**0.130**	**0.138**	**0.128**
Has a washing machine	0.024	0.025	0.023	0.023	0.024	0.022	0.022	0.023	0.021	0.021	0.023	0.021	0.021	0.022	0.021
Has a refrigerator	0.021	0.021	0.021	0.018	0.017	0.018	0.018	0.017	0.018	0.017	0.016	0.018	0.017	0.016	0.018
Has an iron	0.024	0.025	0.024	0.029	0.031	0.028	0.030	0.032	0.029	0.029	0.032	0.029	0.030	0.031	0.029
Has a microwave	0.061	0.068	0.058	0.064	0.071	0.061	0.063	0.069	0.060	0.062	0.069	0.059	0.062	0.068	0.060
Communication	**0.131**	**0.142**	**0.127**	**0.134**	**0.145**	**0.130**	**0.133**	**0.142**	**0.129**	**0.130**	**0.141**	**0.126**	**0.135**	**0.145**	**0.132**
Someone in the home owns a cellphone	0.006	0.004	0.006	0.005	0.003	0.006	0.005	0.003	0.006	0.004	0.003	0.005	0.005	0.003	0.005
Has a landline	0.027	0.030	0.026	0.028	0.031	0.027	0.030	0.033	0.029	0.030	0.033	0.029	0.031	0.034	0.030
Has a desktop computer	0.028	0.031	0.027	0.029	0.032	0.028	0.029	0.032	0.028	0.029	0.032	0.028	0.030	0.033	0.029
Has a laptop	0.022	0.024	0.021	0.023	0.025	0.022	0.021	0.023	0.021	0.021	0.023	0.021	0.023	0.024	0.022
Has a tablet	0.034	0.038	0.033	0.035	0.039	0.034	0.036	0.040	0.035	0.036	0.040	0.034	0.037	0.040	0.035
Has internet	0.014	0.015	0.014	0.013	0.014	0.013	0.012	0.012	0.012	0.010	0.010	0.010	0.010	0.010	0.010
Entertainment and education	**0.142**	**0.155**	**0.138**	**0.145**	**0.158**	**0.140**	**0.146**	**0.158**	**0.141**	**0.146**	**0.160**	**0.140**	**0.149**	**0.161**	**0.144**
Has a conventional color TV	0.007	0.006	0.007	0.007	0.007	0.007	0.006	0.007	0.006	0.007	0.008	0.007	0.008	0.010	0.008
Has an LDC. plasma or LED TV	0.012	0.013	0.012	0.011	0.011	0.011	0.011	0.011	0.010	0.010	0.010	0.010	0.009	0.009	0.009
Has a cable or satellite TV subscription	0.010	0.009	0.011	0.010	0.008	0.010	0.010	0.009	0.010	0.011	0.011	0.012	0.011	0.010	0.011
Has a video player (DVD. blue ray. etc.)	0.024	0.027	0.023	0.028	0.031	0.027	0.032	0.035	0.030	0.032	0.036	0.031	0.034	0.038	0.033
Has an audio player	0.013	0.014	0.012	0.014	0.016	0.013	0.014	0.015	0.013	0.014	0.016	0.013	0.014	0.016	0.013
Has a digital music. video. and image player (mp3. mp4. iPod)	0.038	0.042	0.037	0.038	0.042	0.037	0.037	0.041	0.036	0.035	0.040	0.034	0.036	0.039	0.034
Has a video game console (Play Station. X-BOX. Wii. PSP. Nintendo. Gameboy. etc.)	0.038	0.042	0.036	0.037	0.041	0.036	0.037	0.041	0.036	0.036	0.040	0.034	0.037	0.040	0.035
Temperature regulation	**0.150**	**0.162**	**0.146**	**0.153**	**0.165**	**0.148**	**0.152**	**0.163**	**0.148**	**0.150**	**0.163**	**0.145**	**0.153**	**0.163**	**0.150**
Has air-conditioning	0.071	0.080	0.069	0.072	0.080	0.069	0.072	0.079	0.069	0.072	0.081	0.069	0.075	0.082	0.072
Has an electric fan or handheld fan	0.020	0.017	0.021	0.020	0.018	0.021	0.019	0.017	0.020	0.019	0.017	0.020	0.020	0.017	0.021
Has an electric or gas water heater	0.058	0.065	0.056	0.060	0.067	0.058	0.061	0.067	0.058	0.058	0.065	0.056	0.059	0.064	0.056
Mobility	**0.148**	**0.170**	**0.141**	**0.151**	**0.172**	**0.143**	**0.152**	**0.171**	**0.145**	**0.150**	**0.170**	**0.142**	**0.154**	**0.172**	**0.147**
Has a car	0.100	0.113	0.096	0.102	0.113	0.097	0.103	0.113	0.099	0.101	0.113	0.096	0.104	0.114	0.100
Has a motorbike	0.048	0.057	0.045	0.049	0.058	0.046	0.049	0.057	0.046	0.049	0.057	0.046	0.050	0.057	0.047

M.S. = municipal seats; R.A. = small towns and rural areas.

Appendix 4. Contribution of each indicator in multidimensional energy poverty score by department and capital district (2018–2022)

Department	Area	Access to electricity for a range of services	Modern kitchen fuel	Risk of poor air quality indoors	Ownership of home appliances	Access to communication devices	Ownership of devices used for entertainment and education	Ownership of space heating and cooling devices	Access to private transport
Amazonas	Total	0.063	0.087	0.168	0.127	0.133	0.132	0.142	0.148
	Municipal seats	0.033	0.066	0.172	0.130	0.142	0.145	0.150	0.160
	Small towns and rural areas	0.078	0.099	0.167	0.124	0.129	0.125	0.138	0.141
Antioquia	Total	0.007	0.068	0.157	0.129	0.143	0.156	0.168	0.171
	Municipal seats	0.002	0.042	0.164	0.133	0.144	0.160	0.174	0.181
	Small towns and rural areas	0.009	0.077	0.155	0.128	0.142	0.155	0.166	0.168
Arauca	Total	0.026	0.068	0.159	0.134	0.143	0.158	0.154	0.158
	Municipal seats	0.006	0.056	0.165	0.135	0.146	0.164	0.155	0.172
	Small towns and rural areas	0.040	0.075	0.155	0.133	0.140	0.155	0.153	0.149
Atlántico	Total	0.026	0.068	0.194	0.135	0.133	0.149	0.137	0.158
	Municipal seats	0.000	0.026	0.189	0.145	0.147	0.163	0.151	0.179
	Small towns and rural areas	0.034	0.081	0.196	0.131	0.129	0.144	0.133	0.152
Bogotá	Total	0.013	0.066	0.140	0.140	0.141	0.157	0.170	0.173
	Municipal seats	0.001	0.016	0.149	0.161	0.144	0.163	0.181	0.185
	Small towns and rural areas	0.016	0.078	0.137	0.135	0.141	0.156	0.167	0.170
Bolivar	Total	0.039	0.070	0.194	0.130	0.132	0.145	0.136	0.154
	Municipal seats	0.001	0.039	0.199	0.138	0.144	0.158	0.147	0.173
	Small towns and rural areas	0.056	0.083	0.192	0.126	0.126	0.139	0.131	0.145
Boyacá	Total	0.010	0.097	0.148	0.134	0.135	0.152	0.165	0.159
	Municipal seats	0.001	0.023	0.145	0.151	0.147	0.167	0.181	0.184
	Small towns and rural areas	0.011	0.111	0.149	0.131	0.132	0.149	0.162	0.154
Caldas	Total	0.007	0.084	0.138	0.129	0.143	0.154	0.175	0.170
	Municipal seats	0.002	0.038	0.145	0.143	0.149	0.160	0.181	0.182
	Small towns and rural areas	0.008	0.095	0.136	0.126	0.142	0.153	0.173	0.167
Caquetá	Total	0.056	0.074	0.140	0.136	0.132	0.151	0.161	0.150
	Municipal seats	0.004	0.042	0.149	0.142	0.145	0.166	0.177	0.175
	Small towns and rural areas	0.076	0.087	0.137	0.133	0.127	0.146	0.155	0.139
Casanare	Total	0.060	0.049	0.148	0.138	0.133	0.156	0.163	0.153
	Municipal seats	0.014	0.023	0.164	0.146	0.143	0.167	0.172	0.171
	Small towns and rural areas	0.079	0.059	0.141	0.135	0.129	0.151	0.160	0.145
Cauca	Total	0.023	0.081	0.151	0.139	0.136	0.149	0.165	0.155
	Municipal seats	0.002	0.043	0.145	0.145	0.144	0.162	0.182	0.176

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(*continued*)

Department	Area	Access to electricity for a range of services	Modern kitchen fuel	Risk of poor air quality indoors	Ownership of home appliances	Access to communication devices	Ownership of devices used for entertainment and education	Ownership of space heating and cooling devices	Access to private transport
	Small towns and rural areas	0.029	0.095	0.153	0.137	0.133	0.145	0.160	0.148
Cesar	Total	0.043	0.071	0.186	0.133	0.132	0.147	0.139	0.149
	Municipal seats	0.003	0.034	0.186	0.147	0.145	0.163	0.151	0.173
	Small towns and rural areas	0.056	0.083	0.186	0.128	0.128	0.142	0.135	0.141
Córdoba	Total	0.008	0.094	0.195	0.129	0.135	0.148	0.140	0.152
	Municipal seats	0.002	0.040	0.187	0.142	0.146	0.160	0.151	0.172
	Small towns and rural areas	0.010	0.109	0.197	0.125	0.132	0.144	0.137	0.147
Cundinamarca	Total	0.011	0.072	0.140	0.137	0.142	0.158	0.170	0.170
	Municipal seats	0.005	0.022	0.142	0.154	0.148	0.165	0.180	0.184
	Small towns and rural areas	0.012	0.083	0.140	0.133	0.141	0.157	0.168	0.167
Chocó	Total	0.056	0.074	0.151	0.126	0.138	0.143	0.153	0.158
	Municipal seats	0.013	0.064	0.152	0.126	0.147	0.156	0.167	0.176
	Small towns and rural areas	0.077	0.079	0.150	0.127	0.134	0.137	0.146	0.149
Guainía	Total	0.125	0.089	0.160	0.123	0.119	0.126	0.128	0.131
	Municipal seats	0.067	0.079	0.166	0.130	0.126	0.140	0.141	0.149
	Small towns and rural areas	0.153	0.094	0.157	0.120	0.115	0.118	0.121	0.122
Guaviare	Total	0.078	0.080	0.152	0.134	0.129	0.143	0.151	0.134
	Municipal seats	0.008	0.054	0.174	0.139	0.141	0.158	0.164	0.162
	Small towns and rural areas	0.108	0.092	0.140	0.132	0.124	0.136	0.145	0.122
Huila	Total	0.011	0.087	0.159	0.129	0.139	0.153	0.171	0.151
	Municipal seats	0.003	0.023	0.163	0.144	0.149	0.165	0.179	0.175
	Small towns and rural areas	0.013	0.104	0.158	0.125	0.136	0.150	0.168	0.144
La Guajira	Total	0.150	0.079	0.182	0.118	0.109	0.121	0.117	0.123
	Municipal seats	0.006	0.053	0.190	0.146	0.139	0.155	0.144	0.168
	Small towns and rural areas	0.187	0.086	0.179	0.111	0.102	0.113	0.111	0.112
Magdalena	Total	0.043	0.072	0.192	0.133	0.130	0.145	0.136	0.149
	Municipal seats	0.002	0.042	0.192	0.143	0.143	0.160	0.147	0.171
	Small towns and rural areas	0.059	0.085	0.192	0.129	0.124	0.139	0.131	0.140
Meta	Total	0.054	0.072	0.142	0.135	0.134	0.152	0.162	0.148
	Municipal seats	0.006	0.033	0.154	0.144	0.146	0.165	0.175	0.177
	Small towns and rural areas	0.066	0.082	0.139	0.133	0.131	0.149	0.159	0.141
Nariño	Total	0.011	0.081	0.134	0.150	0.140	0.152	0.167	0.164
	Municipal seats	0.002	0.063	0.136	0.150	0.142	0.157	0.174	0.176

(*continued on next page*)

(*continued*)

Department	Area	Access to electricity for a range of services	Modern kitchen fuel	Risk of poor air quality indoors	Ownership of home appliances	Access to communication devices	Ownership of devices used for entertainment and education	Ownership of space heating and cooling devices	Access to private transport
	Small towns and rural areas	0.016	0.090	0.134	0.150	0.139	0.150	0.164	0.158
Norte de Santander	Total	0.015	0.088	0.161	0.132	0.138	0.152	0.159	0.156
	Municipal seats	0.003	0.045	0.162	0.144	0.145	0.162	0.161	0.177
	Small towns and rural areas	0.019	0.104	0.160	0.127	0.135	0.149	0.158	0.148
Putumayo	Total	0.074	0.066	0.137	0.139	0.132	0.147	0.157	0.148
	Municipal seats	0.004	0.053	0.148	0.144	0.144	0.163	0.176	0.169
	Small towns and rural areas	0.112	0.073	0.131	0.136	0.125	0.139	0.147	0.137
Quindío	Total	0.009	0.074	0.144	0.130	0.142	0.156	0.178	0.168
	Municipal seats	0.013	0.034	0.148	0.140	0.146	0.160	0.181	0.179
	Small towns and rural areas	0.007	0.089	0.142	0.126	0.141	0.154	0.176	0.165
Risaralda	Total	0.009	0.076	0.144	0.131	0.142	0.153	0.176	0.168
	Municipal seats	0.002	0.033	0.156	0.140	0.145	0.159	0.184	0.181
	Small towns and rural areas	0.011	0.087	0.142	0.129	0.141	0.152	0.174	0.165
San Andrés	Total	0.004	0.061	0.198	0.100	0.147	0.162	0.154	0.175
	Municipal seats	0.004	0.061	0.198	0.100	0.147	0.162	0.154	0.175
Santander	Total	0.007	0.085	0.156	0.130	0.138	0.155	0.167	0.162
	Municipal seats	0.002	0.028	0.159	0.142	0.146	0.165	0.178	0.181
	Small towns and rural areas	0.008	0.099	0.155	0.127	0.136	0.152	0.165	0.157
Sucre	Total	0.018	0.092	0.207	0.129	0.129	0.144	0.134	0.147
	Municipal seats	0.002	0.042	0.191	0.146	0.144	0.158	0.148	0.170
	Small towns and rural areas	0.022	0.106	0.211	0.124	0.126	0.140	0.131	0.141
Tolima	Total	0.015	0.081	0.163	0.131	0.136	0.151	0.166	0.159
	Municipal seats	0.003	0.022	0.158	0.144	0.147	0.164	0.181	0.181
	Small towns and rural areas	0.017	0.093	0.164	0.128	0.134	0.148	0.163	0.154
Valle del Cauca	Total	0.017	0.063	0.148	0.134	0.141	0.156	0.174	0.167
	Municipal seats	0.008	0.028	0.159	0.142	0.145	0.160	0.180	0.179
	Small towns and rural areas	0.020	0.074	0.145	0.132	0.140	0.154	0.173	0.163
Vaupés	Total	0.079	0.098	0.161	0.131	0.126	0.130	0.137	0.136
	Municipal seats	0.011	0.092	0.171	0.138	0.135	0.144	0.156	0.154
	Small towns and rural areas	0.110	0.102	0.157	0.127	0.123	0.124	0.129	0.128
Vichada	Total	0.164	0.076	0.153	0.120	0.117	0.124	0.125	0.120
	Municipal seats	0.045	0.067	0.155	0.140	0.138	0.152	0.150	0.152
	Small towns and rural areas	0.216	0.079	0.153	0.111	0.109	0.112	0.114	0.106

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