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Sugarcane Bioelectricity Supply in Brazil: A Regional Concentration and Structural Analysis [†]

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Abstract: Sugarcane products come from agro-industrial biomass that is increasingly used in the Brazilian energy matrix, which is important for the sustainability and diversification of renewable energy sources. This article examines the concentration and structure of the supply of sugarcane bioelectricity in Brazil from 1975 to 2023. It uses information on the quantity and cumulative licensed potential of sugarcane-based thermoelectric plants in operation, available from the National Electric Energy Agency (ANEEL) through its Generation Information System (SIGA). To measure regional concentration, the study considered geographical areas (large regions, states, intermediate regions and municipalities) using the following concentration indicators: the Concentration Ratio, Herfindahl–Hirschman Index, Theil Entropy, Comprehensive Concentration Index, and Hall–Tideman Index. The main results show a high concentration of sugarcane bioelectricity at regional and state levels, with a predominance in the Southeast-Central-West axis. During the period analyzed, the State of São Paulo remained the leader in terms of energy generated by sugarcane thermoelectric plants operating in Brazil. In the intermediate regions, the concentration was moderate, while at the municipal level, the concentration was low, indicating a highly competitive market. It can be concluded that the areas with the highest concentration are strategic for directing investments and guiding public policies for the sugarcane bioelectricity sector, which are priority locations for new opportunities. The identification of the most promising regions contributes to a more efficient development of the sector. Given that, a more equitable distribution of bioelectricity production across the country could enhance Brazil's energy security, reduce regional vulnerabilities, and promote more resilient energy systems.



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1. Introduction

The pursuit of energy generation with low greenhouse gas emissions has emerged as one of the main challenges of sustainability today, which, when formulating the Sustainable Development Goals (SDGs), highlighted SDG 7 (Clean and Affordable Energy) and SDG 13 (Action against Global Climate Change) as targets closely linked to the development of sustainable energy policies. Goal 7 aims to ensure universal access to sustainable energy through investments in renewable sources, energy efficiency, and resilient infrastructure. Goal 13 stresses the urgency of mitigating climate change by promoting the transition to sustainable energy systems [1].

In the last few decades, Brazil, along with the international community, has faced significant challenges in mitigating the adverse impacts of energy generation and aligning its energy policies with the SDGs. Three initiatives stand out in this context: the National Alcohol Program (Proálcool) from the 1970s, the Program to Encourage Alternative Electric Energy Sources (Proinfa), launched in the 2000s, and, more recently, the RenovaBio Program. Proálcool was introduced as a measure to address the oil crises in Brazil. This program encouraged sugarcane cultivation and increased ethanol production to replace gasoline. It aimed to reduce dependence on imported oil, promote ethanol as a vehicle fuel, and support agricultural and regional development [2].

Proinfa focused on the expansion of renewable sources in electricity generation, such as wind power, biomass, and small hydroelectric plants (SHPs). In the latest decade, the country instituted RenovaBio, a biofuel policy aimed at decarbonizing the transport sector. The program sets ambitious greenhouse gas (GHG) emission-reduction targets for fuel distributors, encouraging the production and use of advanced biofuels such as biodiesel and second-generation ethanol [3,4].

The national movements reflect the adoption of clean energy sources in line with SDGs 7 and 13, strengthening energy security and mitigating climate change. The abundance of natural resources in Brazil places the country in a privileged position for using biomass as a source of renewable energy. With a diversified energy matrix, Brazil is an international example of sustainability and commitment to the environment. In 2022, renewable sources represented 88% of the country's domestic electricity supply, especially hydroelectricity, which contributed 64% of the supply, and biomass, which was responsible for 8% of the country's electricity production [5].

Brazil, the world leader in sugarcane production, has great potential for producing bioelectricity, which is a viable alternative for partially replacing fossil fuels. Sugarcane bagasse, a by-product of sugar and ethanol production, is an essential biomass used to generate steam and electricity in the sugarcane bioelectricity sector [6]. Sugarcane bioelectricity promotes decentralized energy generation, contributing to environmental mitigation by reducing greenhouse gas emissions [7–9].

Since 2013, Brazil's sugarcane bioelectricity industry has generated a significant surplus of bioelectricity for the electricity grid, in addition to meeting its own consumption [10]. In 2022, 54% of the sugar and ethanol industries exported electricity to the National Inter-connected System (SIN), totaling 20,200 GWh, which corresponds to 4% of the Brazilian electricity matrix [5]. By promoting the production of clean energy, the sugarcane bioelectricity industry contributes to a more sustainable energy matrix, helps to mitigate climate change, and improves the quality of life in rural areas.

Despite the potential and environmental benefits of bioenergy, the production and distribution of biofuels in Brazil faces challenges related to inequality and concentration. The manufacture of biofuels from sugarcane bagasse is concentrated in the Midwest and

Southeast regions, where the sugarcane industry is more established [11], generating unequal economic and environmental impacts. This concentration has economic and social impacts, causing regional disparities and exposing areas to market fluctuations and external shocks, like changes in international commodity prices [12].

Such concentration can encourage unsustainable land use practices, such as deforestation and monoculture, which have adverse long-term effects on biodiversity and environmental balance. It is essential that bioenergy policies in Brazil seek a more equitable distribution of biofuel production and its benefits, promoting the development of the industry in other regions and ensuring equal sharing of economic and environmental gains [13].

Concentration is an essential parameter for market analysis in any sector, as it encompasses the size of firms and the conditions of entry and exit of participants in a single indicator [14]. According to Resende [15], in order to assess concentration and competition in a specific market structure, indicators are needed that theoretically demonstrate the existing degree of concentration and the configuration of the market in the sector analyzed. The following are among the main studies that have used concentration methods: Coelho Junior, Rezende, and Oliveira [14], to study world exports of forestry products; Coelho Junior et al. [16], to examine the distribution and concentration of firewood production in the state of Paraíba; and Martins et al. [17], to investigate the disparity of plant extraction products in the Northeast in relation to the rest of Brazil. In the sugarcane bioelectricity field, Santos Júnior et al. [18] analyzed the Brazilian concentration of bioelectricity supply in 2019; Coelho Junior et al. [19] carried out a conjunctural analysis (2017 and 2023) of Brazilian sugarcane bioelectricity supply, inferring spatial clusters.

Although some analyses have been carried out on the supply of bioelectricity from sugarcane in Brazil, mainly focusing on installed capacity and regional distribution in specific periods, there is still a significant gap in the comprehensive understanding of the regional and temporal dynamics of the supply of this energy resource over an extended period. Previous studies have focused mostly on the areas of greatest energy availability, without taking into account the structure and evolution of supply in different regions in an integrated manner nor considering the need to expand discussions from a broader space-time perspective.

Given this scenario, this study aims to present a robust methodology for assessing the regional concentration of sugarcane bioelectricity supply, using the Brazilian scenario as a basis. This approach offers essential empirical elements to guide public policies that foster the growth and competitiveness of the sector, contributing to a more sustainable and inclusive energy future in Brazil. Additionally, the proposed methodology can be applied to the analysis of other renewable energy supply chains, providing valuable input for international studies on diversification and security of the energy matrix.

Accounting for this introductory section (Section 1), the manuscript has four sections; the base data for the study and the methodology applied are in Section 2. Section 3 presents the results and discussions, where the implications of the results obtained and their relationship with regional policies and private investments are presented, and Section 4 presents the conclusions and perspectives for future research.

2. Materials and Methods

2.1. Data Used

The data used was obtained from the Management Information System (SIGA) of the National Electric Energy Agency (ANEEL), which refers to the Brazilian supply of agro-industrial sugarcane bioelectricity in operation in Brazil. The period analyzed was from 1975 to 2023, defined based on the continuous availability of consistent data from

1975 onwards, ensuring reliability in the assessment of the sector's evolution [20]. The study assessed the geographical sections of the regions, states, intermediate regions, and municipalities, according to the divisions established by the Brazilian Institute of Geography and Statistics (IBGE) [21].

2.2. Concentration and Inequality Measures

The assessment of concentration requires the use of a variety of indices, addressing the complexity and dimensions associated with the market [22]. As posited by Grubb et al. [23] and Chalvatzis and Rubel [24], the parallel utilization of concentration indices in the energy sector engenders the capacity to discount the diversity uncertainties that are linked to the sector. Given that some indicators are sensitive to the market share of the largest players, other indices may be more sensitive to the number of participants.

In order to measure the concentration of sugarcane agro-industrial bioelectricity supply in Brazil, concentration indicators that have been widely applied in the relevant literature were used [25–27]. These indicators are capable of assessing the sector in relation to the different market dimensions. The following indices were employed: the concentration ratio (CR(k)), the Herfindahl–Hirschman Index (HHI), the Theil Entropy (E), the Comprehensive Concentration Index (CCI), and the Hall–Tideman Index (HTI).

The Concentration Ratio CR(k), expressed by Equation (1), is important in assessing the level of market concentration in a specific economic sector. Equation (1) analyzes the supply of sugarcane bioelectricity in different geographical areas ($k = 1, 2, \dots, n$).

$$CR(k) = \sum_{i=1}^k S_i \quad (1)$$

where CR(k) represents the concentration ratio of the k regions producing sugarcane bioelectricity, and S_i is the market share of i region (state, intermediate region, or municipality) in the supply of sugarcane bioelectricity.

The CR(4) and CR(8) for the states were considered, according to Bain's classification [24], as shown in Table 1. In addition, the CR(20) for the intermediate regions and the CR(30) for the municipalities were analyzed, due to the increase in the number of geographical sections for systematization.

Table 1. Concentration ratio classification [CR(k)].

Level of Concentration	CR(4)	CR(8)
Very High	75% or more	90% or more
Moderately High	65–74.99%	85–89.99%
Moderately High	50–64.99%	70–84.99%
Moderately Low	35–54.99%	45–74.99%
Low	Less than 35%	Less than 45%

Source: Bain [28].

The Herfindahl–Hirschman Index (HHI) was proposed by Hirschman [29] and Herfindahl (1950) [30] and is widely used by regulatory authorities to monitor competitiveness and make policy decisions. Using this index, it is possible to measure industrial concentration encompassing all the regions participating in the supply of sugarcane bioelectricity, using Equation (2):

$$HHI = \sum_{i=1}^n S_i^2 \quad (2)$$

where n is the number of geographical units (regions, states, intermediate regions, or municipalities) where bioelectricity production is analyzed, and S_i is the market share of region i (region, state, intermediate region or municipality) in the supply of sugarcane bioelectricity.

The HHI varies between its lower limit of $1/n$ (minimum concentration) and 1 (maximum concentration). Resende [15] proposed an adjusted HHI (HHI'), Equation (3). This adjustment improves the analysis of the index, since it has the interval $0 \leq HHI' \leq 1$, following the classification in Table 2.

$$HHI' = \frac{1}{n-1}(nHHI - 1); n > 1 \quad (3)$$

Table 2. Classification of the level of concentration of the adjusted Herfindahl–Hirschman Index (HHI').

Market Classification	HHI'
Highly competitive market	$HHI' \leq 0.1$
Market is not concentrated	$0.1 < HHI' \leq 0.15$
Moderate concentration	$0.15 < HHI' \leq 0.25$
High concentration	$HHI' > 0.25$

Source: Coelho Junior et al. [14].

The Theil Entropy Index (E) proposed by Theil is used as an indicator of concentration, as it is a measure used to assess inequality or diversity in a data distribution. According to Resende [15], the E (Equation (4)) measures concentration inversely to the HHI.

$$E = -\sum_{i=1}^n \ln(S_i) \quad (4)$$

where n is the number of participating regions, and S_i is the region's market share i (region, state, intermediate region, or municipality) in the supply of sugarcane bioelectricity.

The E index varies between 0 and $\ln(n)$, with 0 for monopoly conditions and $\ln(n)$ for a homogeneous market [31]. As suggested for the HHI, Resende and Boff [31] indicated the adjusted entropy (E') for atemporal analyses, Equation (5). Thus, the adjusted entropy varies between 0, monopoly (maximum concentration), and 1, perfect competition (minimum concentration).

$$E' = -\frac{1}{\ln(n)} \sum_{i=1}^n S_i \ln(S_i) \quad (5)$$

The Comprehensive Concentration Index (CCI), proposed by Horvath (1970) [32], measures the relative dispersion and absolute magnitude of a market structure, complementing other concentration indicators. This metric quantifies concentration, incorporating companies' shares in a weighted way and seeking to capture a more comprehensive view of the structure. The CCI is calculated by adding the share of the main producer to the sum of the squares of the proportional shares of each region, weighted by a multiplier that reflects the proportional size of the rest of the sugarcane bioelectricity producer market. The index is represented by Equation (6).

$$CCI = S_1 + \sum_{i=2}^n S_i^2 (1 - S_i) \quad (6)$$

where S_1 represents the market share of the main producer, and S_i represents the share of other producers offering sugarcane bioelectricity. The index ranges from 0 (perfect competition) to 1 (monopoly), and its complete classification is shown in Table 3.

Table 3. Classification of the level of concentration of the Comprehensive Concentration Index (CCI).

Market Classification	CCI
Monopoly	$0.8 < CCI \leq 1.0$
High concentration	$0.6 < CCI \leq 0.8$
Moderate concentration	$0.4 < CCI \leq 0.6$
Low concentration	$0.2 < CCI \leq 0.4$
Perfect competition	$0.0 \leq CCI \leq 0.2$

Source: Horvath [33].

The Hall–Tideman Index (HTI), developed by Hall and Tideman [34], is represented by Equation (7). The HTI combines the n elements in the indicator. In this index, the participation of each region receives a weight equal to its ranking in the construction of the indicator, and, so, the emphasis becomes the total number of regions producing sugarcane bioelectricity in operation in the country.

$$HTI = \frac{1}{2 \sum_{i=1}^n (iS_i) - 1} \quad (7)$$

where S_i is the participation of region i (region, state, intermediate region, or municipality) in the supply of sugarcane bioelectricity, n is the number of regions participating in the amount of bioelectricity produced, and i indicates the position occupied by the region in descending order of the amount of bioelectricity produced.

In this way, each region has a weight equal to its ranking in the set. The HTI varies between $1/n$ and 1 approaching the former for a certain number of elements of the same size and reaching 1 in the case of a monopoly (high concentration).

For the descriptive analysis of the data related to the indicators in different geographical areas, the mean, standard deviation, and variance were calculated. These calculations were made for the values of the indicators in each geographical section, with the aim of analyzing the concentration of the data. The mean summarizes the central tendency of the indicators in each region. The standard deviation and variance assess dispersion and variability relative to the mean, aiding in a detailed understanding of their geographical concentration [35].

3. Results and Discussion

Table 4 presents the evolution of the power granted to agro-industrial sugarcane bioelectricity thermoelectric plants in operation in Brazil, broken down by region and state, from 1975 to 2023. It observes a concentration of thermoelectric plant production in the state of São Paulo, inferring the dominance of the Southeast region. Next, there has been significant growth in the Midwest region in recent years.

Over the years, the production of sugarcane bioelectricity has increased in Brazilian regions. It can be seen that the increase occurred unevenly between regions, resulting in a process of spatial concentration. The state of São Paulo contributed, on average, 67.74% of the accumulated power granted (MW), showing a variance of 1.91% during the period evaluated. The Southeast's predominance is attributed to the economic strength, agricultural mechanization, São Paulo's productive capacity, and the favorable geographical and climatic conditions. São Paulo accounts for 89.73% of the Southeast region and 74.72% of Brazil, with a variance of 0.73% over the period studied [36]. It is worth noting the investments and growth, since 2005, in the state of Minas Gerais, which has strengthened the Southeast region. These investments attracted groups from other states and foreign investors. They also enabled the mechanization of production, the creation of storage and

transport systems, and the use of correctives for the Cerrado’s acidic soils, all of which were crucial for the sector’s development [37,38].

Table 4. Evolution of the accumulated granted power (MW) of sugarcane-based thermoelectric plants in operation in Brazil, divided into regions, from 1975 to 2023.

Regions/States	1975	1985	1995	2005	2015	2023
Southeast	223.55	976.01	1609.51	3022.62	6973.71	7748.41
Espírito Santo	0.00	33.00	33.00	66.00	66.00	66.00
Minas Gerais	0.00	0.00	46.00	279.81	1293.80	1575.40
Rio de Janeiro	0.00	0.00	0.00	0.00	44.00	44.00
São Paulo	223.55	943.01	1530.51	2676.81	5569.91	6063.01
West Central	7.30	70.20	137.40	427.22	2584.98	2752.17
Goiás	7.30	35.20	75.20	211.72	1325.25	1430.75
Mato Grosso	0.00	0.00	27.20	94.70	167.40	189.10
Mato Grosso do Sul	0.00	35.00	35.00	120.80	1092.33	1132.33
Northeast	22.00	143.71	206.52	415.52	832.02	884.02
Alagoas	0.00	37.30	69.61	140.81	288.31	328.31
Bahia	0.00	16.00	16.00	16.00	16.00	16.00
Paraíba	0.00	0.00	30.50	101.50	101.50	101.50
Pernambuco	22.00	69.41	69.41	136.21	278.21	290.21
Piauí	0.00	0.00	0.00	0.00	28.50	28.50
Rio Grande do Norte	0.00	21.00	21.00	21.00	61.00	61.00
Sergipe	0.00	0.00	0.00	0.00	58.50	58.50
South	0.00	35.00	84.50	148.68	504.68	567.28
Paraná	0.00	35.00	84.50	148.68	504.68	567.28
North	0.00	20.00	20.00	20.00	100.00	100.00
Pará	0.00	20.00	20.00	20.00	20.00	20.00
Tocantins	0.00	0.00	0.00	0.00	80.00	80.00
Brazil	252.85	1244.91	2057.93	4034.04	10,995.37	12,051.87

Source: ANEEL [20].

The Central-West region is the second largest in terms of granted power (MW), contributing an average of 12.03% and showing a variation of 0.67%. It is particularly noteworthy that there has been an increase in thermoelectric plants and power capacity in the states of Goiás and Mato Grosso do Sul over the past decades. The expansion of the sugarcane bioelectricity sector in Brazil’s Central-West region is driven by multiple factors. High solar radiation and government incentives for clean energy play a key role. Environmental awareness, technological advancements, and increasing electricity demand further contribute to this growth. Additionally, investments in research and innovation, the sector’s intrinsic characteristics, and its expansion in the Cerrado biome reinforce this development. These elements have collectively contributed to the strengthening of the sector in the region [39,40].

The Northeast, South, and North regions contribute 9.13% ($\pm 0.02\%$), 3.32% ($\pm 0.03\%$), and 0.8% ($\pm 0.002\%$), respectively, demonstrating an inequality in bioelectricity production. There have been no significant structural changes in sugarcane bioelectricity; new production hubs have emerged from traditional areas. The lower contributions from the Northeast, South, and North regions highlight the need for more effective public policies to promote real decentralization and more balanced and inclusive regional development [40].

This growth observed in the sugar-energy sector, in addition to private investment, was strongly associated with the establishment of incentive programs for the use of renewable energies, such as the Brazilian Alcohol Program—ProÁlcool (1975), the Incentive

Program for Alternative Sources of Electricity—PROINFA (2022), and the National Biofuels Policy—RENOVABio (2017) [41]. According to Santos [42], several incentives may have resulted in the growth of the sugarcane bioelectricity sector. These include the granting of public credit to finance production and logistics, the establishment of tax incentives to reduce production costs and make sugar and ethanol prices more attractive, and the creation and maintenance of public RD&I institutions. The training of qualified labor has also been a contributing factor.

Figure 1 illustrates the evolution of the Concentration Ratio for sugarcane bioelectricity production and supply in Brazil from 1975 to 2023. It highlights changes in the geographical distribution of production at various levels over the decades. These graphs illustrate trends in the concentration of bioelectricity in specific regions of Brazil, reflecting changes in the production dynamics of the Brazilian sugarcane bioelectricity sector, with a direct impact on the energy supply in various locations.

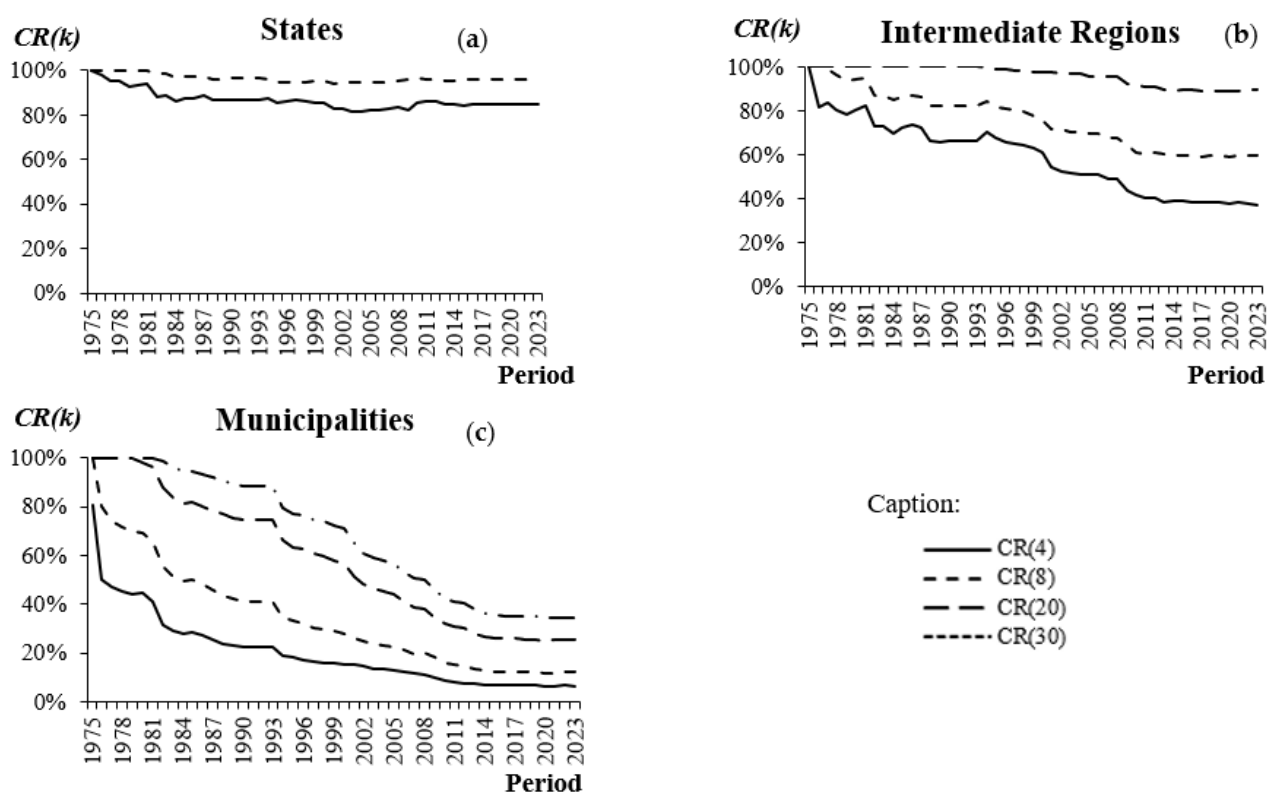


Figure 1. Evolution of the Concentration Ratio for sugarcane bioelectricity production and supply in the states (a), intermediate regions (b) and municipalities (c) of Brazil, from 1975 to 2023.

Figure 1a indicates that $[CR(4)_{State}]$, during the period analyzed, had an average of 86.79% ($\pm 0.17\%$), while $[CR(8)_{State}]$ shows 96.42% ($\pm 0.03\%$), which characterizes very high concentration in both cases [24]. In 1975, $CR(4)$ was made up of just three states: São Paulo, Pernambuco, and Goiás, showing a limited geographical distribution and total monopoly. The following year, in 1976, the indicator was expanded to four states, now including Pernambuco (PE), Alagoas (AL), and Rio Grande do Norte (RN), in addition to São Paulo (SP). The presence of the northeastern states highlights the growing importance of the Northeast region in the production of sugarcane bioelectricity in the country. Sugarcane cultivation is deeply rooted in the Northeast, where the hot and humid climate favors cultivation, and the production of sugar and ethanol plays a crucial role in the local economy [19].

On the other hand, CR(8) was only completed for the first time in 1982 and maintained a high concentration throughout the studied period. In 2023, the last year of the studied period, CR(4) was composed solely of states from the Southeast and Central-West regions, specifically São Paulo, Minas Gerais, Goiás, and Mato Grosso do Sul, in that order of hierarchy. It is important to note that this analysis includes only 17 of the 27 federative units in Brazil (26 states and the Federal District), according to IBGE, which are involved in the production of sugarcane bioelectricity through the operation of agro-industrial thermoelectric plants, influencing the high concentration rate identified.

In Figure 1b, [CR(4)Inter] had an average of 58.45%, characterizing a moderate concentration [28]. During the initial years, from 1975 to 1999, CR(4) exhibited a high concentration, with 73.02% of the supply. This period showed moderate changes in the concentration pattern, reflected in a standard deviation of 0.16200 and a variance of 0.02624. These values indicate moderate variations due to the growing investment and development of the sector from the 2000s onwards. This growth resulted from government programs to encourage renewable energy during the oil crisis period [43]. From 2014 onwards, [CR(4)Inter] began, for the first time, to show a moderately low concentration, with values below 40% [24], a scenario that continued until 2023. The intermediate regions that contributed most to the CR(4) were Ribeirão Preto (SP), São José do Rio Preto (SP), Rio Verde (GO), and Dourados (MS), standing out as the largest producers with the highest accumulated power granted.

The CR(8)Inter presented an average of 75.69%, indicating a very high concentration [28]. The coefficient showed moderate changes in the concentration pattern, with a standard deviation of 0.13019 and a variance of 0.01695, due to discrepancies in the initial value when compared to the accumulated power in 2023. CR(20)Inter had an average of 96.03% over the period analyzed, showing few changes in the concentration pattern, with a standard deviation of 0.04417 and a variance of 0.00195. Although it also indicates a very high concentration according to Bain [28], the usefulness of the CR(20)Inter for analysis is limited. This high concentration is already evident in the CR(8)Inter. At this juncture, of the 133 intermediate regions named by the IBGE, only 40 were considered, around 30% of the intermediate regions. This explains the high CR(20)Inter concentration index, since 29 of these intermediate regions are located on the Southeast-Central-West axis, which concentrates approximately 87.13% of the power granted, as shown in Table 4. Table 5 shows the CR(20)Inter power granted, based on 2023, and its evolution since 1975. Only three intermediate regions are not part of the regional axis with the highest concentration in Brazil: Maringá (PR), Recife (PE), and Maceió (AL).

There has been significant growth since 2005, driven by incentive programs for renewable energy, such as Proálcool [44]. The intermediate region of Ribeirão Preto (SP), a pioneer in sugarcane bioelectricity, leads the way in terms of concentration, accounting for 14.27% of the country's total power. With a high concentration of sugarcane mills that use bagasse as the main source of biomass for electricity generation, Ribeirão Preto has become one of the main hubs in the sector in Brazil. The region hosts important events such as Fenasucro & Agrocana, the largest bioenergy fair in the world, which promotes innovations and discussions about the future of the sector [45]. The Ribeirão Preto intermediate region has 37 projects in operation in the agro-industrial sector, most notably the Bonfim and Bela Vista plants, with capacities of 111 MW and 97 MW, respectively.

Of the 10 main intermediate regions, which together account for 67.18% of the concentration of accumulated power granted, 9 are located in the Southeast/Central-West axis. Maringá (PR) stands out as the only representative from the South, due to its strategic location in a sugarcane producing area, advanced infrastructure, and investments in innovation and sustainability. Recent studies indicate that converting pastures to sugarcane in Maringá has been an agronomically viable strategy, contributing to an increase in soil carbon stocks

and the mitigation of greenhouse gas emissions. In addition, government policies aimed at improving livestock productivity have freed up pasture areas for sugarcane production. This has been achieved without compromising food production or putting pressure on natural ecosystems. These factors consolidate Maringá as the most important region in the South in this sector [46].

Table 5. Evolution of the accumulated granted power (MW) of the sugarcane-based thermoelectric plants in operation in Brazil, in the 20 main intermediate regions (based on 2023), from 1975 to 2023.

Rank	Intermediate Regions	1975	1985	1995	2005	2015	2023
1	Ribeirão Preto (SP)	73.00	338.32	625.92	983.62	1645.37	1720.37
2	São José do Rio Preto (SP)	0.00	204.24	369.24	459.75	1064.35	1120.85
3	Rio Verde (GO)	0.00	0.00	0.00	15.00	777.03	827.03
4	Dourados (MS)	0.00	0.00	0.00	85.80	776.00	816.00
5	Uberaba (MG)	0.00	0.00	0.00	210.81	650.91	775.91
6	Bauru (SP)	0.00	0.00	87.30	259.90	623.90	772.93
7	Presidente Prudente (SP)	0.00	0.00	0.00	96.78	556.93	591.93
8	Araçatuba (SP)	0.00	18.00	26.00	110.00	459.00	564.00
9	Maringá (PR)	0.00	15.00	64.50	110.28	418.28	480.88
10	Campinas (SP)	150.55	225.55	265.15	353.65	353.65	426.65
11	Araraquara (SP)	0.00	131.90	131.90	226.10	361.70	361.70
12	Marília (SP)	0.00	25.00	25.00	187.02	355.02	355.02
13	Uberlândia (MG)	0.00	0.00	0.00	15.00	244.80	349.80
14	Campo Grande (MS)	0.00	35.00	35.00	35.00	316.33	316.33
15	Recife (PE)	22.00	69.41	69.41	136.21	278.21	290.21
16	Maceió (AL)	0.00	37.30	69.61	131.31	225.81	265.81
17	Itumbiara (GO)	0.00	0.00	0.00	46.52	208.02	216.52
18	Porangatu–Uruaçu (GO)	7.30	7.30	47.30	122.30	200.30	200.30
19	Divinópolis (MG)	0.00	0.00	0.00	0.00	140.00	191.60
20	São Luís de Montes Belos-Iporá (GO)	0.00	6.20	6.20	6.20	118.20	165.20

Source: ANEEL [20].

These factors highlight the region's prominence as a vital center for sugar-energy bioelectricity, making a significant contribution to Brazil's energy matrix and to sustainable development [47]. Coelho Junior et al. [19], using the Scan statistics methodology, identified productive agglomerations in the northern São Paulo region, driven by the availability of raw materials and skilled labor. This broader geographic concentration not only enhances industrial efficiency and reduces logistical costs but also strengthens supply chain integration, further solidifying Ribeirão Preto as a strategic center for Brazil's sugar-energy and bioelectricity industry.

The regional concentration identified in this study aligns with the findings of Santos Junior et al. [18], who analyzed the forest bioelectricity sector in Brazil. Despite focusing on a different energy source, their results remain relevant to sugarcane bioelectricity. Growth in this sector is strongly linked to the pursuit of sustainable energy alternatives, cost reductions, and the adoption of techno-environmental principles, such as the circular economy. The concentration of bioelectricity production in regions with high agricultural productivity and well-developed processing infrastructure underscores the importance of understanding the spatial distribution and structural patterns that shape this energy source.

Recife (PE) and Maceió (AL) stand out as the most prominent intermediate regions in the Northeast, with continuous growth driven by a developed infrastructure, incentive policies, advanced technologies, and a tradition in sugarcane production. The Northeast region offers valuable opportunities for the expansion of bioelectricity. This is due to its vast sugarcane production in the humid Atlantic coastal area and the availability of biomass

from agricultural and urban waste. The use of these non-traditional biomass sources can diversify and increase the regional supply of bioenergy, contributing to the mitigation of greenhouse gas emissions and promoting local socio-economic development [48]. Although most sugarcane production in Brazil has been concentrated in the state of São Paulo in recent years, Recife, and Maceió have established themselves as powerhouses and references in the sugarcane bioelectricity sector in the Northeast [49]. This demonstrates that investing in this form of energy in the region can strengthen the national electricity system and provide significant environmental and economic benefits.

Figure 1c demonstrates that CR(4)Munic averaged 20.14% between 1975 and 2023, characterizing a low concentration [28]. From 1982 onwards, the CR(4) was below 35%, which indicates a low concentration. The coefficient showed moderate changes in the concentration pattern, with a standard deviation of 0.14935 and a variance of 0.02231. The municipalities that contributed to the composition of the CR(4) during the period analyzed, Rio Brilhante (MS), Valparaíso (SP), Guaíra (SP), and Pirassununga (SP), stand out as the largest producers with the highest accumulated power granted, three of which are in the state of São Paulo. Although São Paulo is the main producer of licensed power in Brazil, in Table 6, the municipality with the most licensed power is Rio Brilhante, in Mato Grosso do Sul. This municipality tops the list in terms of accumulated power among all the municipalities analyzed. Although São Paulo stands out in terms of total production, generation capacity is more decentralized at the municipal level within the state. This highlights both the collective strength of the municipalities and the investments directed towards state and regional development [50].

Table 6. Evolution of the accumulated granted power (MW) of the sugarcane-based thermoelectric plants in operation in Brazil, in the 20 main municipalities (based on 2023), from 1975 to 2023.

Rank	Municipalities	1975	1985	1995	2005	2015	2023
1	Rio Brilhante (MS)	0.00	0.00	0.00	73.80	303.80	303.80
2	Valparaíso (SP)	0.00	0.00	8.00	8.00	153.00	203.00
3	Guaíra (SP)	0.00	56.72	56.72	56.72	201.72	201.75
4	Pirassununga (SP)	0.00	80.50	80.50	150.50	195.50	195.50
5	Pitangueiras (SP)	0.00	43.00	76.00	146.00	190.00	190.00
6	Frutal (MG)	0.00	0.00	0.00	0.00	70.09	170.09
7	Quirinópolis (GO)	0.00	0.00	0.00	96.78	164.50	164.50
8	Pontal (SP)	0.00	75.00	86.50	161.00	161.00	161.00
9	Chapadão do Céu (GO)	0.00	0.00	0.00	0.00	160.00	160.00
10	São Joaquim da Barra (SP)	0.00	0.00	71.00	71.00	104.00	154.00
11	Goianésia (GO)	7.30	7.30	7.30	72.30	150.30	150.30
12	Ariranha (SP)	0.00	108.80	108.80	108.80	148.80	148.80
13	Promissão (SP)	0.00	0.00	0.00	58.40	138.40	138.40
14	Barra Bonita (SP)	0.00	0.00	0.00	0.00	136.00	136.00
15	João Pinheiro (MG)	0.00	0.00	0.00	46.00	136.00	136.00
16	Narandiba (SP)	0.00	0.00	0.00	0.00	131.30	131.30
17	Macatuba (SP)	0.00	0.00	80.30	80.30	80.30	130.30
18	Caçu (GO)	0.00	0.00	0.00	0.00	130.00	130.00
19	Nova Alvorada do Sul (MS)	0.00	0.00	0.00	0.00	130.00	130.00
20	Ivinhema (MS)	0.00	0.00	0.00	0.00	80.00	120.00

Source: ANEEL [20].

CR(8)Munic showed an average of 34.20% over the period analyzed, which is also characterized as a low concentration [28]. The coefficient showed moderate changes in the concentration pattern, with a standard deviation of 0.21483 and a variance of 0.04615. CR(20)Munic had an average of 57.73% and was considered moderately high. The coeffi-

cient indicated a standard deviation of 0.2600 and variance of 0.06760. For CR(30)Munic, the average was 68.12%, indicating a high concentration with a standard deviation of 0.23830 and variance of 0.06165. The high values showed that a group of municipalities dominated the agro-industrial production of sugarcane biomass, since, of the 226 municipalities that took part in this analysis, only 30 municipalities held 68.12% of the total power granted. Table 6, referring to the CR(20)Munic for 2023, indicates that the 20 municipalities with the highest accumulated power granted over the period analyzed are concentrated in the Southeast/Central-West axis, as proposed by the study.

Figure 2 shows the evolution of the Herfindahl–Hirschman Index (HHI) for the production and supply of sugarcane bioelectricity at different regional levels, from 1975 to 2023. At the regional level (Figure 2a), the indicator registered the most concentrated market, the [HHI]_{region}, with an average of 0.5847, a standard deviation of 0.07761, and a variance of 0.00602. The largest difference between the HHI and the Lower Limit was 0.4679 in 1994, and the smallest was 0.2587 in 1976. For the state level (Figure 2b), the [HHI]_{state} had an average of 0.4797, with a standard deviation of 0.1245 and a variance of 0.01550. The biggest difference between the curves was 0.5143 in 1994, and the smallest was 0.2381 in 2022.

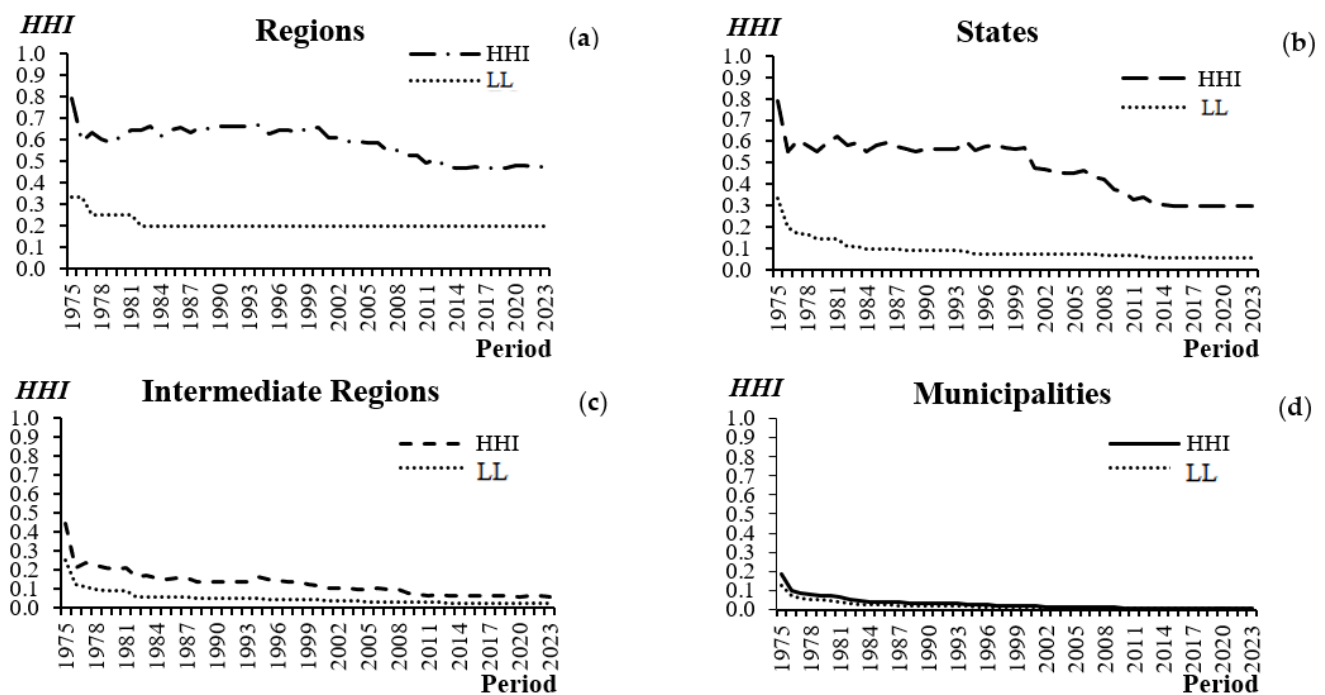


Figure 2. Evolution of the Herfindahl–Hirschman Index (HHI) for sugarcane bioelectricity production (a) and supply in the states (b), intermediate regions (c) and municipalities (d) of Brazil, from 1975 to 2023.

At the intermediate level (Figure 2c), the [HHI]_{inter} had an average of 0.1279, a standard deviation of 0.06815, and a variance of 0.00464. The highest concentration was in 1975, with a difference of 0.1963 between the HHI and the Lower Limit (LL), and the lowest concentration was in 2020, with a difference of 0.0347. At the municipal level (Figure 2d), the [HHI]_{munic} had a mean of 0.0312, standard deviation of 0.03196, and variance of 0.00102. The largest difference between the curves was 0.0605 in 1975, and the smallest was 0.0026 in 2020. The Lower Limit for the state level showed a mean of 0.0921, standard deviation of 0.04712, and variance of 0.00222. For the intermediate level, the Lower Limit had a mean of 0.0506, standard deviation of 0.03719, and variance of 0.00138. And, for the municipal level, the Lower Limit had a mean of 0.0200, standard deviation of 0.02175, and

variance of 0.00047. The proximity of the HHI line to the Lower Limit, especially at the municipal level, indicates a more competitive market, with a low concentration of market power, reflecting significant fragmentation and lower concentration [51].

This analysis indicates higher concentration at the regional level, reflecting an uneven distribution of sugarcane bioelectricity production across broader areas. The declining concentration trend, especially at the state level, suggests a gradual dissemination of bioelectricity generation as a reflection of policies promoting diversification and broader market participation.

Figure 3 presents the evolution of the Entropy Index (E) for the production and supply of sugarcane bioelectricity from 1975 to 2023, at different regional levels. At the regional level (Figure 3a), the Entropy and Upper Limit (UL) curves indicate a slight upward trend in concentration, followed by stabilization. The average Entropy was 0.8198, with a variance of 0.01603, suggesting that the increase in concentration was limited and stable. The proximity between the E and UL curves indicates a balanced distribution of production between the regions, without major disparities in the supply of bioelectricity.

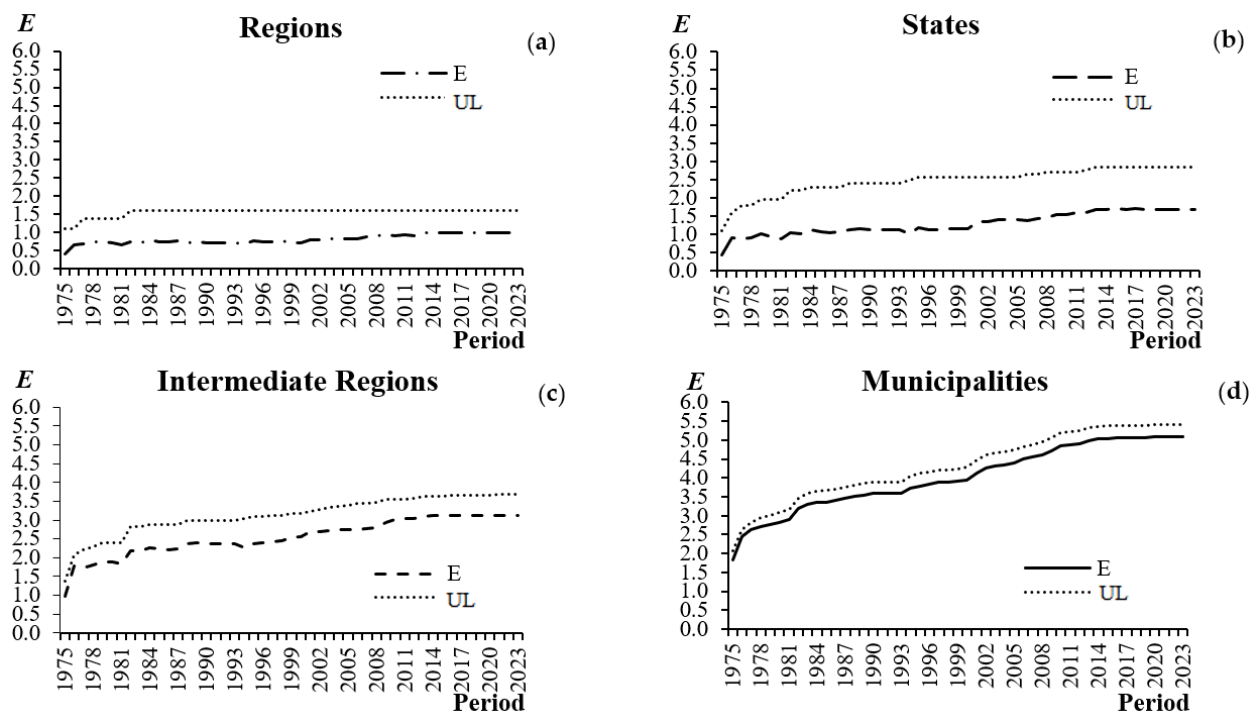


Figure 3. Evolution of the Entropy Index (E) for the production (a) and supply of sugarcane bioelectricity in the states (b), intermediate regions (c) and municipalities (d) of Brazil, 1975 to 2023.

At the state level (Figure 3b), the curves show a sharper increase in concentration, with an average Entropy of 1.2864 and a variance of 0.30133. This indicates greater centralization of production in certain states, resulting from the strategic location of the plants, regional incentive policies, or the availability of resources. At the intermediate regional level (Figure 3c) and the municipal level (Figure 3d), the Entropy and UL curves are closer, indicating less concentration of production. At the intermediate regional level, the average Entropy was 2.5464, with a variance of 0.2334, while at the municipal level, the average Entropy reached 4.01021, with a variance of 0.72092. These data suggest that, at more disaggregated levels, bioelectricity production is more distributed and diversified, reflecting a lower concentration and greater equity in supply [52]. Evidence of this phenomenon of deconcentration at less aggregated levels has the potential to inform the creation of policy

measures that could lead to the decentralization of production. Such measures may in turn have a positive impact on increasing energy security in other regions of the country.

Figure 4 shows the evolution of the Adjusted Herfindahl–Hirschman Index (HHI'), Adjusted Entropy (E'), Comprehensive Concentration Index (CCI), and Hall–Tideman Index (HTI) in the production and supply of sugarcane bioelectricity in Brazil across different geographical levels from 1975 to 2023. Figure 4a shows that, for the regions, the HHI' had an average of 0.4744, with a standard deviation of 0.0945 and a variance of 0.0089, indicating a highly concentrated market [31]. For the states, the average of this indicator was 0.4307, with a standard deviation of 0.1193 and a variance of 0.0142, also indicating high concentration, although to a lesser degree compared to the regions. The HHI' provides a comprehensive assessment of market concentration, considering all participants, whereas the CR(k) only focuses on a specific part of the market.

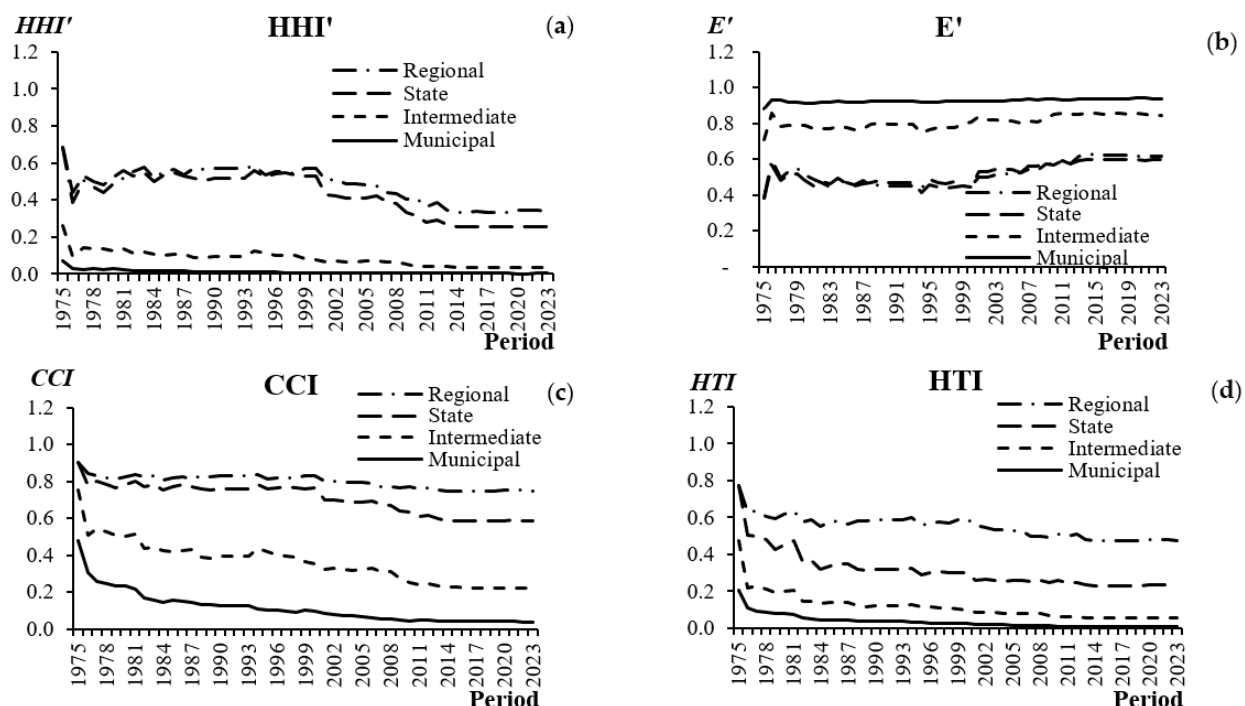


Figure 4. Evolution of the Adjusted HHI (HHI') (a), Adjusted Entropy (E') (b), Comprehensive Concentration Index (CCI) (c), and Hall–Tideman Index (HTI) (d) in the production and supply of sugarcane bioelectricity in Brazil across different geographical levels from 1975 to 2023.

For the intermediate regions, the average HHI' was 0.0829, with a standard deviation of 0.0419 and a variance of 0.0018, indicating a highly competitive market. In relation to the municipalities, the HHI' showed an average of 0.0117, with a standard deviation of 0.0691 and a variance of 0.0001, also demonstrating a competitive market [16]. In this context, the low concentration indicated by the HHI' for municipalities is in line with the observations of the CR(k), which also points to high competitiveness and market dispersion at the municipal level. This correspondence occurs because both indices, HHI' and CR(k), reflect the distribution of market concentration on a more detailed scale. They show a competitive and dispersed environment in the municipalities, in contrast to the more evident concentration in more aggregated analyses, such as those carried out for regions and states.

The Adjusted HHI (HHI') reached its maximum values in 1975 for all the geographical levels analyzed. For the regions, the HHI' was 0.6851, while for the states, the maximum value was also 0.6851, and, for the intermediate regions, it was 0.0356. In the municipal-

ities, the maximum value recorded was 0.0691. This period was characterized by high concentration in the sugarcane bioelectricity sector, reflecting a market dominated by a small number of large plants and low levels of competition. In contrast, the minimum HHI' values occurred in 2015 for regions (0.3318), states (0.2530), and intermediate regions (0.0356), and in 2020 for municipalities (0.0026). The sharp reduction in concentration from 2015 onwards can be attributed to a significant expansion in the number of plants and increased competition in the sector. This development was driven by policies to encourage the diversification of bioelectricity supply and the inclusion of new technologies and players in the market. The 2020s saw greater dispersion at the municipal level, reflecting an even deeper fragmentation of the market and an increase in local competition, due to the emergence of new plants and the strengthening of decentralization policies and regional incentives.

The adjusted entropy (E'), Figure 4b, shows that the regions had the highest concentration among the sections analyzed, with an average value of 0.5230. The highest E' value recorded was 0.6267 in 2015, while the lowest was 0.3857 in 1975. This increase in concentration in 2015 can be attributed to market consolidation and the greater participation of large mills, resulting in a more monopolistic market structure. For the states, the average E' was 0.5161, with values close to those found for the regions, indicating a high concentration and similar monopoly characteristics in the sugarcane bioelectricity sector. The changes observed over time reflect a market which, although competitive in some years, has had periods of greater concentration dominated by large players, in line with the general trend of market dominance in the sector [31]. The proximity of the values for states and regions suggests a uniformity in concentration at broader geographical levels.

Within the analysis, the intermediate regions and municipalities showed market characteristics close to ideal competition. For the intermediate regions, the average Adjusted Entropy (E') was 0.8077, with a standard deviation of 0.0356 and a variation of 0.0013. The highest concentration value was 0.7085 in 1975, and the lowest was 0.8567 in 2014. These values indicate a relatively small variation, reflecting a market with characteristics closer to ideal competition. For the municipalities, the average value of E' was 0.9256, with a standard deviation of 0.106 and a variation of 0.0001. The highest concentration value recorded was 0.8784 in 1975, and the lowest was 0.9405 in 2020. These values also suggest that the municipal market remained within a range close to ideal competition throughout the period analyzed [52]. Although there are no specific ranges for the classification of E' , the values presented show that both the intermediate regions and the municipalities have maintained a relatively stable level of competition, with a market concentration that has approached the ideal in many years.

From the CCI graph, Figure 4c, a notable similarity in the behavior of the regional and state coefficients was observed. At the regional level, a high concentration was noted, as the CCI_{region} achieved an average of 0.7995, a standard deviation of 0.0353, and a variance of 0.0012. For the CCI_{state} , an average of 0.7074 was obtained, with a standard deviation of 0.0817 and a variance of 0.067, indicating a high concentration, although less concentrated than at the regional level. The intermediate regions and municipalities, as shown by the graph's behavior, both display low concentration, indicating a competitive market. The CCI_{inter} had an average of 0.3588, a standard deviation of 0.1122, and a variance of 0.0126, suggesting a low-concentration market. Meanwhile, the municipalities show an average value of 0.1135, a standard deviation of 0.0845, and a variance of 0.0071, indicating the highest competitiveness in the market according to this CCI indicator analysis. This fits within perfect competition according to Horvath's [33] classification.

The analysis of the HTI graph, Figure 4d, shows that all levels exhibit the same behavior, although in different proportions. For the regions, the HTI_{region} had an average

participation of 0.5505, with a standard deviation of 0.0599 and a variance of 0.0036, indicating the highest concentration at the regional level during the analyzed period. For the states, the HTI_state recorded an average value of 0.3131, a standard deviation of 0.1004, and a variance of 0.0101, indicating low concentration. On the other hand, the HTI_inter had an average of 0.1149, a standard deviation of 0.0706, and a variance of 0.0500, also indicating low concentration. As for the HTI_munic, it presented an average value of 0.0342, with a standard deviation of 0.0347 and a variance of 0.0012. This indicator showed the most significant decline trends, with its value being very close to 0 in the last years of the analysis, indicating the lowest concentration at the regional level and perfect competition [34].

The simultaneous application of indicators was crucial for understanding the structure of bioelectricity supply in Brazil [53]. When evaluating the energy market in the European Union, Chalvatzis and Ioannidis [26] pointed out that the combined use of market indicators is indispensable for comparing countries and benchmarking energy security. The results of concentration analyses can show how certain resources, such as biomass, can contribute to growing the mix and increasing national energy security. Busu [27] also described the importance of complementary measures when evaluating a market and recognizing the competitive structure when studying the biomass market in Romania.

The indices revealed a strong concentration of bioelectricity production in the Southeast-Central-West axis, with a particular emphasis on the state of São Paulo, which leads in terms of the number of sugarcane-based thermoelectric plants and installed potential. This concentration reflects not only the sector's growth but also the spatial distribution of supply, influenced by local competitive advantages and policies and programs promoting bioelectricity [54]. According to Coelho Junior et al. [19], in 2023, the Southeast region maintained its leadership, while the Central-West region demonstrated increasing potential due to sugarcane expansion, reinforcing the concentration of granted power in these two regions.

The results found are also in line with those of Cervi et al. [55], who highlighted the great potential for bioelectricity supply in the state of São Paulo. According to the authors, traditional sugarcane growing regions tend to have an impactful bioenergy network, and the existence of an optimized industrial and logistical structure facilitates the establishment of companies in the field. The national supply structure of sugarcane bioelectricity in Brazil is strongly shaped by locational and regional factors, with areas of higher generation density benefiting from spatial clustering. These findings are consistent with those reported by Santos Junior et al. [48], who identified that regions characterized by higher supply density tend to derive competitive advantages from spatial groupings, such as enhanced infrastructure efficiency, reduced logistical costs, and strengthened local supply chains, ultimately contributing to greater efficiency and sustainability within the sector.

Although the spatial concentration of bioelectricity offers competitive advantages, it also presents challenges for the sector's sustainable expansion. Beyond structural issues, the viability of new ventures depends on overcoming regulatory and logistical barriers. In Brazil, the primary risks associated with investments in this sector pertain to site selection, environmental licensing, and grid connection, particularly in remote areas [18].

Identifying areas with the greatest potential for bioelectricity generation, considering locational and infrastructural factors, is essential for mitigating risks and optimizing energy planning [56]. The results indicate that regions with more developed infrastructure and technological capacity tend to offer greater investment security, reinforcing the role of spatial analysis as a strategic tool for decision-making in the sector.

Finally, the establishment of new production chains for bioelectricity, in addition to the economic, security, and energy diversity aspects, also contributes to the national

decarbonization process. According to the Brazilian Energy Transition Program [57], biomass, especially sugarcane, is responsible for around 20% of the carbon neutrality in the national energy matrix (electricity + primary supply), and its potential could be increased through the relevant use of BECCS (Bioenergy with Carbon Capture and Storage). In this way, national investments should be even more important in the coming decades, and market studies can guide these new investments [58].

4. Conclusions

Based on the analyses carried out, it can be concluded that there was significant growth in the supply and production of sugarcane bioelectricity in Brazil between 1975 and 2023. However, observation of different geographical areas showed this growth occurred unevenly, with a high concentration in the Southeast and Midwest regions.

The CR(k) of supply at the state level showed a high concentration. For the intermediate regions, there was a moderately high to very high concentration, and for the municipalities there was a low concentration. The HHI showed low concentration for municipalities, which indicates high competitiveness at the municipal level and moderate concentration for intermediate regions. As for the states and regions, there was high concentration for the state of São Paulo and the Southeast and Center-West regions.

The adjusted Entropy Index showed low concentration for municipalities, considering an atomized market, low concentration for intermediate regions, and high concentration for states and regions. The ICC showed high concentration for the regions and states, low concentration for the intermediate regions, and the level of perfect competition for the municipalities, with low concentration during the period analyzed. The Hall–Tideman Index showed high concentration for the regions, moderate concentration for the states, and low concentration for the intermediate regions and municipalities.

Even though the distribution at the municipal level is considered fair, the high concentration in the Southeast and Midwest regions suggests a competitive advantage for these areas over others, potentially attracting further investments in the sector. The pursuit of knowledge and technological spillover tends to direct strategic actions toward these identified competitive hubs, reinforcing regional disparities in the industry's growth.

The results of this study offer valuable insights for public policy planning aimed at fostering a more balanced spatial distribution of the sugarcane bioelectricity sector. To enhance the applicability of these results, it is important to align them with national and international energy policy frameworks, particularly those focused on the expansion of renewable energy, environmental sustainability objectives, and energy security. A more equitable distribution of bioelectricity production across the country could enhance Brazil's energy security, reduce regional vulnerabilities, and promote more resilient energy systems. Such alignment could serve as a foundation for targeted interventions that optimize sectoral development while ensuring broader economic and environmental benefits.

Future research could explore long-term projections for the development of bioelectricity in Brazil, assessing its strategic advantages relative to other renewable sources, such as photovoltaics and wind power. In addition, examining the environmental impacts of the sector's expansion, the integration of circular economy principles, and its role in advancing Brazil's energy transition could generate valuable insights. On a global scale, the methodology employed in this study may serve as a reference for evaluating the spatial-temporal distribution and competitiveness of biomass-based energy or other renewable sources in different national frameworks.

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data curation, B.H.C.d.O. and E.P.S.J.; writing—original draft preparation, L.M.C.J., B.H.C.d.O., F.F.D. and E.P.S.J.; writing—review and editing, L.M.C.J., B.H.C.d.O., F.F.D., I.Y.B.A.S., V.B.S., F.S. and E.P.S.J.; visualization, L.M.C.J., B.H.C.d.O., F.F.D., I.Y.B.A.S., V.B.S., F.S. and E.P.S.J.; supervision, L.M.C.J. and E.P.S.J.; project administration, L.M.C.J. All authors have read and agreed to the published version of the manuscript.

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