Concentration and Spatial Clustering of Forest-Based Thermoelectric Plants in Brazil

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ABSTRACT This study analyzes the concentration and conglomerate spatial distribution of forest-based thermoelectric plants in Brazil, in 2018. Herein, we spatially identified thermoelectric plants in different Brazilian regions and states, and measured the state concentrations (levels 1 and 2 of forest) using various indicators, including the concentration ratio ($CR(k)$), the Herfindahl-Hirschman index (HHI), Theil's entropy (E), and the Gini coefficient (G). Meanwhile, each state's conglomerates were evaluated using the Scan statistic. We found that there are 98 forest-base thermoelectric plants in Brazil, most of which are located in the south-central portion of the country where there is rapid forest growth. The southern region contains 32.65% of the identified plants as a result of the presence of level 2 forest resources (black liquor and forest waste). Regarding the state's concentration (forest level 1), $CR(k)$ revealed a moderate concentration, the HHI and E indices demonstrated low concentrations, and G suggested null to weak inequality. Of these Brazilian forest bioelectricity plants (level 1), 4 clusters were identified, but only one was statistically significant, located in the southern region. Concerning level 2 sources, the only statistically significant conglomerate regarding charcoal was centered in Açailândia (Maranhão). These findings will provide information to assist industry decision-making processes and help guide public policies for forest bioelectricity development in Brazil that favor energy security and improve resource utilization.

INDEX TERMS Bioenergy, forest economy, market study.

I. INTRODUCTION

Forest biomass is recovered from planted and native forest management, urban afforestation, recuperated wood, and industrial processes by product [1], [2]. This energetic resource can be utilized in traditional heating and food cooking processes or modern methods, such as biofuels and electricity. Forest resources are economically competitive and have thus become a strategic option for diversification and energy matrix security while maintaining the current CO_2 level in the atmosphere [3].

In 2016, according to the International Energy Agency [4], the world's primary energy supply was 13,760 MToe (million tons of oil equivalent), of which 1,349.29 MToe (9.8%) was

Industrial economic researchers have collaborated to evaluate how industries interact and perform. Measuring the used for heat production, which is an equivalent of 7.59 of the total biomass. Further, in 2016, worldwide electricity generation was 9,594,341 GWh, of which 570,574 GWh was produced from biomass obtained from solid biofuels (64.75%), biogas (14.84%), urban and agricultural waste (12.60%), industrial waste (6.40%), and liquid biofuels (1.41%).

Brazil's 2016 electricity generation was 578,889 GWh, of which biomass contributed 50,642 GWh (8.7%) [5]. According to the National Electric Energy Data System, the total installed capacity in 2017 was 165.20 GW, wherein 14.50 GW were contributed from biomass, specially derived from agro-industry (77.47%), forest (21.56%), urban waste (0.91%), animal waste (0.03%), and liquid biofuels (0.03%). concentrations of certain industries is crucial for
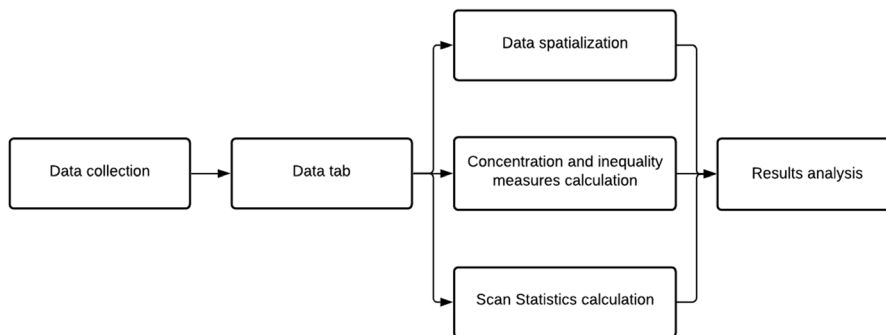
FIGURE 1. Flowchart of the proposed research.

competition analyses and understanding a certain company's control over their commodity, which involves considering supply and demand, technological development, and worker qualifications [5]. According to Possas [6], this determined concentration behaves inversely to competition, wherein low competition is a result of a high concentration among the participants in a certain sector.

According to Porter [7], conglomerate analyses are crucial in regional economic studies. A conglomerate evaluation considers factors such as suppliers of raw materials, components, machines, services, and specialized suppliers. In spatial economy studies, the Scan statistic constitutes a method used for clusters' identification and analysis [8], [9].

Relating to industrial concentration research, this study highlights: Chalvatzis and Ioannidis [10], Charumbira and Sunde [11], Coelho Junior [12], [13], Coelho Junior *et al.* [14]–[20], Mohammed *et al.* [21], Nawrocki and Carter [22], Selvatti *et al.* [23], and Van Egeraat *et al.* [24]. Regarding special conglomerate analyses, we emphasize: Arroyo *et al.* [25], Lieu *et al.* [26], Nigatu *et al.* [27], Randolph [28], and Yih *et al.* [29]. Thus, in order to understand market dynamics and guide policymakers in the energy sector, this study conducted concentration and conglomerate analyses of forest thermoelectric plants in Brazil for 2018.

II. MATERIAL AND METHODS

A. OBJECT OF STUDY
Herein, research was conducted in a specific sequence of steps, as shown in Fig. 1. The data of based forest thermoelectric plants, both with ascription and in operation, were obtained from the Information Generation Bank (BIG) of the National Electric Energy Agency (ANEEL) for 2018. These power plants were spatialized with QGIS 3.6.0®, using geographic coordinates taken from Google Maps.

An analysis of the forest-based thermoelectric plants spatial distribution in Brazil was performed to observe level 1 (forest) and level 2 [charcoal, blast furnace gas (BFG), firewood, black liquor (BL), and forest waste (FW)] plants according to the information provided by the BIG [30].

B. CONCENTRATION MEASURES AND INEQUALITY
According to Charumbira and Sunde [11], a concentration analysis uses indicators concerning the particularities, complexities, and dimensions connected with the market. These indicators can be classified as partial or summary. The partial indices consider a portion of the data, whereas the summary indices use all the values included in the study [14]. Herein, the indicators used were the concentration ratio (CR), the Herfindahl-Hirschman index (*HHI*), Theil's entropy (E), and the Gini coefficient (G).

The CR (k) analyses the market share of the k (k = 1, 2, . . . , n) Brazilian states with the largest amount of based forest thermoelectric plants (levels 1 and 2). It can be determined using the following [31]:

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

where, S_i is the market share of states with a quantity of forest-based thermoelectric plants (levels 1 and 2). The concentration of the four [$CR(4)$] and eight [$CR(8)$] states with the largest quantity of forest-based thermoelectric plants was calculated and analyzed using the data summarized in Table 1. In addition, the main [$CR(1)$] and two largest [$CR(2)$] states were included in this analysis.

TABLE 1. Classification of concentration ratio (CR) of the four [CR (4)] and eight [CR (8)] states with the largest quantity of forest-based thermoelectric plants (levels 1 and 2).

Level of concentration	Four largest	Eight largest
Very high	$CR(4) \geq 75\%$	$CR(8) \geq 90\%$
High	$65\% \leq CR(4) < 75\%$	$85\% \leq CR(8) < 90\%$
Highly Moderate	$50\% \leq CR(4) < 65\%$	$70\% \leq CR(8) < 85\%$
Low Moderate	$35\% \leq CR(4) < 50\%$	$45\% \leq CR(8) < 70\%$
Low	$CR(4) < 35\%$	$CR(8) < 45\%$

Source: Bain [31].

The Herfindahl-Hirschman Index (HHI), (2), is based on the sum of the squared market share of states that have the forest-based thermoelectric plants (levels 1 and 2). The HHI range varies between 1/n (lower limit) and 1, 1/n meaning that

all the states are equally distributed as one atomized market and 1 meaning a monopolized situation [32]–[34].

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

In (2), S_i is the market share of states with the quantity of forest-based thermoelectric plants (levels 1 and 2) and n denotes the total number of states with forest-based thermoelectric plants. Resende [35] proposed a tailored *HHI* (*HHI'*) for intertemporal evaluations (3) that ranges between 0 and 1. Values of *HHI'* < 0.10 denote an atomized market, $0.10 \leq HHI' \leq 0.15$ denotes a non-concentrated market, $0.15 \leq HHI' \leq 0.25$ denotes a moderately concentrated market, and *HHI'* > 0.25 denotes a concentrated market.

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

As proposed by Theil [36], *E* was developed based on an information theory and can be used as a concentration indicator. According to Resende [35], *E* (4) measures concentration inversely to HHI.

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

where S_i is the market share of states with a quantity of forest-based thermoelectric plants (levels 1 and 2), and n is the number of total states with forest-based thermoelectric plants. This index ranges between 0 to ln(n), wherein 0 represents a monopoly condition and ln(n) denotes a homogenic market. Similar to the *HHI*, Resende and Boff [37] suggested a tailored *E* (E') (5)) to maintain an interval of 0 (monopoly) to 1 (atomized market).

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

As proposed by Gini [38], G was originally used as a measurement to verify population income inequality. Currently, G (6) is applied in different fields.

$$G = 1 - \frac{\left[\sum_{i=1}^{n} (S_{ij} + S_i) \right]}{n}, \qquad (6)$$

where S_{ij} is the cumulated market share of i states with a quantity of forest-based thermoelectric plants (levels 1 and 2), S_i is the market share of states with a quantity of forest-based thermoelectric plants (levels 1 and 2), and n is the total number of states with forest-based thermoelectric plants.

G can be classified based on its results. It shows null to weak inequality in the range of 0.000 – 0.250, weak to average inequality for 0.251 – 0.500, average to strong inequality for 0.501 – 0.700, strong to very strong inequality 0.701 – 0.900, and very strong to absolute inequality for values of 0.901 – 1.000.

C. SCAN STATISTIC

To determine the Scan Statistic, a purely spatial analysis of the high conglomeration was used based on a probabilistic model of Poisson and maximum similarity under a *Z* region divided in sub-regions *m* [9]. The identified parameters include the candidate zone for the cluster (*z*) in Brazil, the probability the forest-based thermoelectric plants exist in the interior (*p*) or outside (*q*) of *z*. Note that (7) is the null hypothesis (*p* = *q*), as given by the similarity function. (L_0) [8].

$$L_0 = \frac{e^{-C}}{C!} \left(\frac{C}{N} \right)^{C} \prod_{j=1}^{m} n(j), \qquad (7)$$

where *C* is the total of forest-base thermoelectric plants in Brazil, *C!* is the factorial of the forest-based thermoelectric plants, *N* is the total number of electricity generators in Brazil (including hydraulic and thermal power), and *n(j)* is the total of electricity generators in each sub-region j. Equation (8) is the alternative hypothesis (*p* > *q*) given by the similarity function [L(z,p,q)] [8].

$$L(z, p, q) = \frac{e^{[-pn(z) - q(N - n(z))]}}{C!} p^{C(z)} q^{C - C(z)} \prod_{j=1}^{m} n(j), \quad (8)$$

where *n(z)* is the total number of electricity generators in *z*, and *C(z)* is the number of forest-based thermoelectric plants in *z*. Finally, (9) determines the likelihood ratio in *z* [*LR(z)*].

$$LR(z) = \frac{L(z, p, q)}{L_0}$$

$$= \begin{cases} \left(\frac{C(z)}{\mu(z)} \right)^{c(z)} \left(\frac{C - C(z)}{\mu(z)} \right)^{C - c(z)}, & se \frac{C(z)}{\mu(z)} > 1, \\ 1, & otherwise, \end{cases} \qquad (9)$$

where μ_z is the expected value of the forest-based thermoelectric plants under the null hypothesis

The likelihood logarithm ratio ($\log[LR(z)] = LLR(z)$) was used to stabilize the variance, and the associated circular windows within 25% of the forest-based electricity generator units in the *z* region. The *LLR(z)* results were then used in a Monte Carlo simulation (9.999 replications) at a significance less than 5% (*p-value* < 0.05) using (10) [27], [39].

$$value\ p = \frac{Ranking}{(1 + \#replications)}, \qquad (10)$$

where *Ranking* is the classification of *LLR(z)*. The relative risk (RR) (11) is the probability that the forest-based thermoelectric plants are in the interior of the cluster [8].

$$RR = \frac{i/E[i]}{(C - i)/(E[C] - E[i])} \qquad (11)$$

where *E[C]* is the mathematical hope of the forest biomass thermoelectric plants, *i* is the quantity of forest-based thermoelectric plants inside the cluster, and *E[i]* is the mathematical hope of the forest-based thermoelectric plants inside

the cluster. The characteristics of the identified clusters were evaluated using the centroid of the conglomerate, the radius (R, km), observed value (Obs.), expected value (Exp.), RR, *LLR*, and *p-value*.

III. RESULTS AND DISCUSSION

Fig. 2 shows the spatial distribution of forest-based thermoelectric plants in Brazil in 2018. In total, 98 power plants were identified, wherein the southern region had the largest proportion (32.65%), containing FW (25), BL (6), and firewood plants (1).
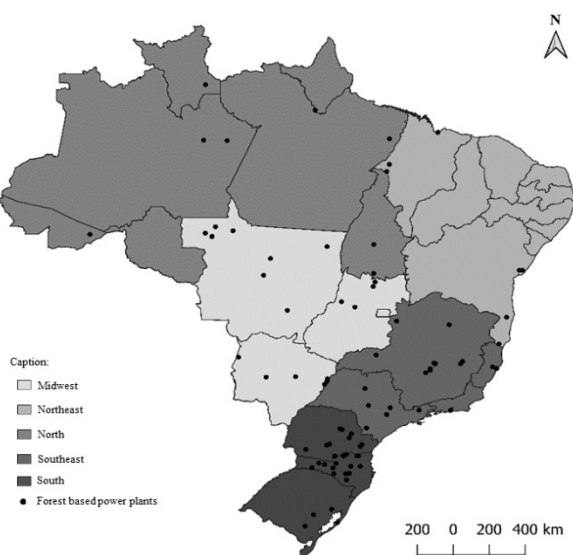

FIGURE 2. The spatial distribution of forest-based thermoelectric plants in Brazil, in 2018. Source: Elaborated by authors with information from ANEEL [30].

In the southeast (28.57%), forest bioelectricity generation consisted of BFG (9), FW (7), charcoal (5), BL (4), and firewood (3). In the Midwest (17.35%), FW (12) plants prevailed, followed by BL (3), and BFG (2). In the north (12.24%) thermoelectric plants used FW (10), BL (1), and firewood (1). Finally, in the northeast region (9.18%), plants used BL (4), charcoal (3), BFG (1), and FW (1). According to the Brazilian Institute of Trees (IBÁ) [40], planted forest areas mainly exist in the mid-southern portion of the country, wherein approximately 80% are eucalyptus plantations and 20% are pines. These forest massifs are mainly used to produce cellulose and paper, wood panels, laminate flooring, sawn wood, and charcoal.

Table 2 introduces the state ranking with forest-based thermoelectric plants (levels 1 and 2) in Brazil, in 2018. The biomass from level 1 (forest) is contributed by the thermoelectric plants (level 2) in the following proportions: FW (56.12%), BL (18.37%), BFG (12.25%), charcoal (8.16%), and firewood (5.10%). Of the 27 federal units, 17 states (62.96%) had power plants that used forest bioelectricity, mainly Minas Gerais, Santa Catarina, and Paraná, which

together comprised 44.89% of the total thermoelectric plants in the country.

Minas Gerais has the highest ranking with 18 thermoelectric plants and use of all the level 2 sources, which is mainly attributed to the state's link with the steelmaker sector with BFG (50%), specifically the companies Usiminas, Calsete, Usiminas 2, Valinho, Metalsider, Plantar, Siderúrgica União, Siderúrgica Barão de Mauá, and Sidepar. Concerning FW (22.22%), the contributing companies were Cargill Uberlândia, Fazenda Santa Marta, Natureza Limpa, and Rações Patense (Itaúna). Regarding charcoal (16.66%), AVG I-II, Cisam, and Usipar were the main contributing companies. Finally, BL (5.55%) was used by Cenibra.

Santa Catarina occupied the second position with 16 thermoelectric plants, of which 81.25% used forest waste (Battistella, Berneck Curitibanos, Bragagnolo, CATIVA I, Chapecó, Energia Madeiras, Iguaçu-Ibicuí-Termo-1-2-4, Irani, Lages–Engie, Rigesa, Rohden, Terranova I, and Thermoazul), and 18.75% used BL (Celulose Irani, Klabin Correia Pinto, and Klabin Otacílio Costa). Finally, Paraná in the third position had 10 thermoelectric plants that used forest bioelectricity, with 80% of the energy produced from FW contributed by the Berneck, Dois Vizinhos, Ecoluz, Energy Green, Miguel Forte, Piraí, Pizzatto, and Santa Maria companies, and 20% from BL from the Klabin and Klabin Celulose companies.

Considering only level 2 forest bioelectricity, we noticed that 62.50% of the charcoal use for electricity generation that occurred in the southeast was attributed to the states of Minas Gerais (Cisam, Usipar, and AVG I-II), Espirito Santo (João Neiva), and Rio de Janeiro (Usitrar Eco-Energy Rio). Meanwhile, the remaining 37.50%, which occurred in the northeast, was attributed to Maranhão (Simasa, Viena, and Gusa Nordeste). In relation to BFG, the southeast represented 75% of the studied power plants, all of which existed in Minas Gerais (Usiminas, Calsete, Usiminas 2, Valinho, Metalsider, Plantar, Siderúrgica União, Siderúrgica Barão de Mauá, and Sidepar). The next largest BFG region was the Midwest (16.67%), followed by the northeast (8.33%), wherein power plants existed in Mato Grosso do Sul (Vetorial Corumbá and Vetorial), and Maranhão (Usitrar), respectively. These power plant types (charcoal and BFG) revealed an association with steel companies, which identified electricity as a co-product to the sector.

The bioelectricity supply from firewood showed a lower quantity of thermoelectric plants among level 2 sources, primarily occurring in the states of São Paulo (Orsa and Citrus), Tocantins (Granol PO), Minas Gerais (Algar Agro), and Rio Grande do Sul (Marfrig São Gabriel RS). Regarding BL, the south comprised the largest portion (33.33%) as determined by the Celulose Irani, Klabin Otacílio Costa, and Klabin Correia Pinto power plants located in Santa Catarina, the Klabin Celulose and Klabin plants in Paraná, and the CMPC Brasil in Rio Grande do Sul. In the northeast (22.22%), Bahia displayed the largest participation with the power plants Bahia Pulp, Suzano Mucuri, and Veracel,

TABLE 2. Forest-based thermoelectric plants state rankings (levels 1 and 2) in Brazil (2018).

Ranking	States	Level 2					Level 1
		Charcoal	BFG	Firewood	BL	FoW	Forest
1º	Minas Gerais (MG)	3	9	1	1	4	18
2º	Santa Catarina (SC)	-	-	-	3	13	16
3º	Paraná (PR)	-	-	-	2	8	10
4º	Mato Grosso (MT)	-	-	-	-	9	9
5º	Pará (PA)	-	-	-	1	6	7
6º	São Paulo (SP)	-	-	2	2	3	7
7º	Mato Grosso do Sul (MS)	-	2	-	3	1	6
8º	Rio Grande do Sul (RS)	-	-	1	1	4	6
9º	Maranhão (MA)	3	1	-	1	-	5
10º	Bahia (BA)	-	-	-	3	1	4
11º	Amazonas (AM)	-	-	-	-	2	2
12º	Goiás (GO)	-	-	-	-	2	2
13º	Espírito Santo (ES)	1	-	-	1	-	2
14º	Tocantins (TO)	-	-	1	-	-	1
15º	Roraima (RR)	-	-	-	-	1	1
16º	Acre (AC)	-	-	-	-	1	1
17º	Rio de Janeiro (RJ)	1	-	-	-	-	1
	Brazil	**8**	**12**	**5**	**18**	**55**	**98**

Caption: BFG = Blast Furnace Gas; BL = Black Liquor; FW = Forest Waste.
Source: ANEEL [30].

TABLE 3. Forest-based thermoelectric plants indicators of state concentration in Brazil, in 2018.

Indicator	Level 2					Level 1
	CH	GBF	Firewood	Black Liquor	FoW	Forest
CR(1)	37.50%	75.00%	40.00%	16.67%	23.64%	18.37%
CR(2)	75.00%	91.67%	60.00%	33.33%	40.00%	34.69%
CR(4)	100%	-	100%	61.11%	65.45%	54.08%
CR(8)	-	-	-	88.89%	89.09%	80.61%
HHI	0.313	0.597	0.280	0.124	0.133	0.103
LI	0.250	0.333	0.250	0.100	0.077	0.059
HHI'	0.083	0.396	0,040	0.026	0.061	0.047
E	1.255	0.721	1.332	2.187	2.232	2.487
LS	1.386	1.099	1.386	2.3026	2.565	2.833
E'	0.906	0.657	0.961	0.950	0.870	0.877
G	0.250	0.222	0.200	0.478	0.610	0.640
n	4	3	4	10	13	17

Caption: BFG = Blast Furnace Gas; FW = Forest Waste; *CR(k)* = Concentration Ratio; *HHI* = Herfindahl-Hirschman Index; *LI* = Inferior Limit; *HHI'* = Tailored Herfindahl-Hirschman; E = Theil's Entropy, LS = Superior limit; G = Gini Coefficient; n = states number.

whereas in the Midwest (22.22%), Mato Grosso do Sul had participation from the Fibria MS, Fibria MS-II and ElDorado Brasil plants.

Among the remaining level 2 sources, FW was used in all the studied regions and in 13 federation states. Specifically, the southern region represented 45.45% of the forest-based thermoelectric plants, attributed mainly to Santa Catarina (23.64%) from its thermal plants of Rigesa, Engie Lages, and Berneck Curitibanos. The Midwest (21.82%), which has 9 power plants in Mato Grosso, was contributed to mainly

by Guaçu, F&S AgriSolutions, and the Primavera do Leste companies.

In Table 3, the state concentration indicators of forest-based thermoelectric plants (levels 1 and 2) in Brazil are listed (2018). Brazil has great forest product availability (native and planted). However, it must transform its comparative advantages into competitive advantages in order to leverage national forest bioelectricity development.

According to the CR of forest bioelectricity (level 1), the *CR(1)* was 18.37% and *CR(2)* was 34.69%, wherein the

main states are Minas Gerais and Santa Catarina, respectively. Thus, there was a highly moderate concentration in *CR(4)* at 54.08%, and in *CR(8)* at 80.61%. When *CR(4)* is greater than 40% participation market, the structure is oligopolistic [41]. The *HHI'* result (0.047) deduced an atomized market. Hence, an oligopoly with extreme competition was affirmed. The index *E'* corroborates the *HHI'* interpretation, showing a non-concentrated market with a *E'* value of 0.877. Moreover, the results of *G* (0.640) showed an average to strong inequality. Further, by separating the forest bioelectricity level 1 to level 2 and examining the results, we determined the following:

1. In relation to charcoal thermoelectric plants, 4 states participated. *CR(1)* had a value of 37.50%, wherein Maranhão and Minas Gerais had 3 power plants each. Consequently, *CR(2)* was 75% and *CR(4)* was 100%, therefore revealing a high concentration. The difference between the *HHI* (0.313) and LI (0.250) values showed an approximately homogeneous market, confirming the 0.083 *HHI'* value, which suggests an atomized market. The result of *E'* (0.906) showed a low concentration between participants, and *G* was classified to have a null to weak inequality, as 2 states have the same proportion (37.5%) and 2 have 12.5%.

2. Among the forest biomass thermoelectric plants (level 2), BFG was the least used among the Brazilians states, owing to the steel sector's peculiar characteristics. Although Brazilian green steel production uses charcoal, which allows for a cleaner process, co-generation requires structural and technological changes to provide energy efficiency gains. Thus, the charcoal power plants in Minas Gerais contained 75% [*CR(1)*] of the BFG power plants, wherein its *HHI'* value (0.396) indicated its high concentration, as confirmed by *E'* (0.657). Conversely, the result of *G* (0.222) indicated a null to weak inequality without observing a significant difference among the participants.

3. The firewood thermoelectric plants in the states presented a very strong concentration, wherein *CR(1)* was 40%, *CR(2)* was 60%, and *CR(4)* was 100%. However, *HHI'* revealed an atomized market (*HHI'* < 0.10). Moreover, *E* (1.332) with LS (1.386) both showed low concentration. Nevertheless, the index *G* (0.200) demonstrated null to weak inequality.

4. The BL thermoelectric plants in the states presented a *CR(4)* of 61.11%, classifying it to have a high to moderate concentration. Of the 10 participants, the states that contribute to this *CR(4)* value are Bahia (3), Mato Grosso Sul (3), Santa Catarina (3), Paraná (2), and São Paulo (2). Further, the *CR(8)* identified a high concentration (88.89%). Moreover, the *HHI'* (0.026) and *E'* (0.950) values suggested an atomized market, while *G* (0.478) revealed weak to average inequality among the states.

5. From the level 2 sources, the FW thermoelectric plants contributed the most (55) existing in 13 Brazilian states. Santa Catarina had the largest participation with a *CR(1)* of 23.64%, which when combined with Mato Grosso, became a *CR(2)* of 40%. The *CR(4)* and *CR(8)* values of 65.45%

and 89.09%, respectively, showed a high state concentration. When examining the summary indices, an approximation between the *HHI* (0.133) and *LI* (0.077) was noted. This indicates a non-concentrated market, and the *HHI'* value (0.061) suggests an atomized market. Moreover, the results of *E'* (0.87) confirmed using the *HHI'* approach as it is near to 1. The *G* index was found to be 0.610, inferring an average to strong inequality.

Fig. 3 shows clusters of forest-based thermoelectric plants in Brazil, both levels 1 and 2, in 2018. Regarding the forest-base thermoelectric plants (Fig. 2(a)) 4 clusters were identified, wherein the south hosted the cluster with the most expressive influence. The main charcoal thermoelectric plant conglomerates (Fig. 2(b)) are located in the southeast. Fig. 2(c) shows that there are two BFG clusters, with conglomerates in the far west of the Midwest region and the northeast. Regarding firewood, only one cluster was identified. It includes all the Brazilian regions, except the south (Fig. 2(d)). In relation to BL (Fig. 2(e)) two clusters were found, the first located between the northeast and southeast regions, justified by the cellulose and paper industrial hub in the south of Bahia and the second was composed of all the states from the southern region, wherein 35.3% of the BL power plants existed. Fig. 2(f) illustrates the FW, displaying clusters in the Midwest, southeast, and southern regions.

Table 4 summarizes the cluster characterization of forest-based thermoelectric plants in Brazil, in 2018. The first cluster has a radius of 649.87 km, with its center in São Gabriel (RS city), wherein 45 plants were identified. Although 24.5 plants were expected, the RR was 2.53. This cluster covered Paraná, Rio Grande do Sul, Santa Catarina, São Paulo, and the southern part of Mato Grosso. The remaining clusters did not introduce significance according to the *p-value*. However, cluster 3 is of note, with a radius of 815.67 km and center in Açailândia (MA), it has 9 power plants as a result of the large number of steel companies.

According to the determined *p-values*, only the charcoal cluster, centered in Açailândia, was statistically significant, having a 1.15 km radius and 3 power plants. Although the remaining conglomerates could have occurred by chance, the highlights regarding BL are cluster 1, centered in Mucuri (BA) with a radius of 296.81 km and 4 power plants, and cluster 2, centered in Otacilio Costa (SC) with a 368.54 km radius and 6 power plants.

Regarding FW, cluster 1, which was centered in Primavera do Leste (MT city) with a radius of 595.24 km and 6 power plants, had the largest LLR value (4.38) and a 4.73 RR. Cluster 2, which was centered in Curitiba (PR city) had the largest observation number with 12 power plants, of which only 5.7 were expected, and a RR of 2.41. Simioni *et al.* [42] showed that the planted forest gravity centers in Brazil that are used for the production of firewood are in the southern region and that of charcoal are in Minas Gerais.

According to the IBÁ [43], in 2016, approximately 65% of the planted forests in Brazil were located in the south and southeast regions to meet the demands of cellulose and
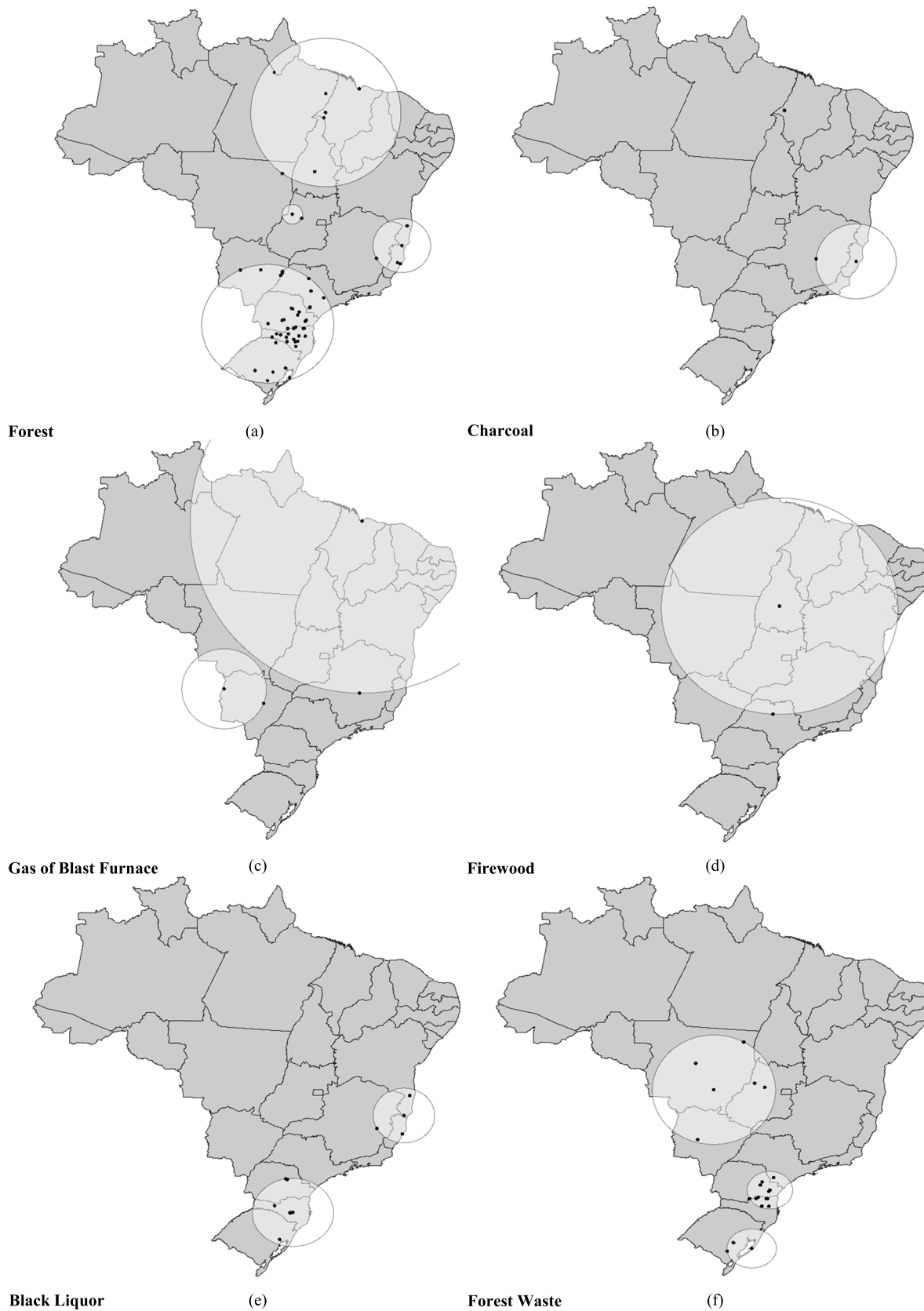
Forest (a)

Charcoal (b)

Gas of Blast Furnace (c)

Firewood (d)

Black Liquor (e)

Forest Waste (f)

FIGURE 3. Clusters of forest-based thermoelectric plants in Brazil (2018).

TABLE 4. Clusters characterization of forest-based thermoelectric plants (levels 1 and 2) in Brazil (2018).

		Cluster	Center	R (km)	Obs.	Exp.	RR	LLR	*p-value*
Level 1	**Forest**	1	São Gabriel (RS)	649.87	45	24.57	2.53	9.90	0.0013
		2	Mucuri (BA)	296.81	5	0.71	7.34	5.55	0.1073
		3	Açailândia (MA)	815.67	9	3.41	2.80	3.30	0.6517
		4	Araguapaz (GO)	108.09	2	0.43	4.76	1.53	0.9965
Level 2	**CH**	1	Açailândia (MA)	1.15	3	0.42	10.70	3.79	0.025
		2	João Neiva (ES)	409.35	2	0.28	9.08	2.40	0.097
	GBF	1	Corumbá (MS)	436.41	2	0.43	5.44	1.63	0.321
		2	José de Ribamar (MA)	1876.78	2	1.28	1.68	0.20	0.994
	FW	1	Porto Nacional (TO)	1175.03	2	0.71	4.00	0.99	0.333
	BL	1	Mucuri (BA)	296.81	4	1.14	4.21	2.41	0.256
		2	Otacílio Costa (SC)	368.54	6	2.57	3.00	2.07	0.415
	FoW	1	Primavera do Leste (MT)	595.24	6	1.39	4.73	4.38	0.179
		2	Curitiba (PR)	204.67	12	5.70	2.41	3.05	0.521
		3	Mostardas (RS)	211.76	3	0.62	5.09	2.42	0.707

Caption: CH = Charcoal; BFG = Blast Furnace Gas; FW = Firewood, BL = Black Liquor; FoW = Forest Waste; R= radius; LLR = likelihood logarithm ratio; Obs. = observed cases; Exp. = expected cases; RR = relative risk.

paper companies in the southern region and the Minas Gerais steel companies. Ericsson *et al.* [44] and Broughel [45] determined that forest bioelectricity supply in Finland, Sweden, and the United States was strongly related to forest-based industries.

IV. CONCLUSION

Based on these findings, we determined that the southern region has the largest number of forest-based thermoelectric power plants in Brazil, wherein BL and FW are the main power plants inputs in the country.

The state concentrations of level 1 (forest) presented moderate concentrations via *CR* (*k*) and low *HHI*, *E*, and *G* values. Regarding charcoal, a low concentration was verified. Meanwhile, BFG was the least used kind of power plant among the Brazilian states, nevertheless presenting a strong concentration in Minas Gerais. Regarding firewood, the summary indices suggested an atomized market. The use of BL was classified by low concentration values of *HHI* and E, and a moderate *G*. FW dominated the number of power plants and the most states utilized this source, characterizing it as with weak *HHI'* and *E'* concentration values, and an average to strong concentration of *G*. In total, there are 4 clusters of forest biomass in Brazil, only one of which is considered significant, which is located in the southern region.

Regarding level 2 sources, only one cluster, centered in Açailândia (MA), had statistical significance for charcoal. Nevertheless, while they did not have statistical significance,

the BL clusters centered in Mucuri (BA) and Otacílio Costa (CS) were noted. Meanwhile, the main FW clusters were those in Primavera do Leste (MT) and Curitiba (PR), which were the result of a high number of identified cases.

In this study, we examined information regarding the potential centers of forest bioelectricity generation in thermoelectric plants throughout Brazil that apply cogeneration for economic subsistence to achieve efficiency gains in supplies use (level 1), and the best results of level 2 applications. This research will help future studies regarding the business viability of electric energy generation and will foment economic and regional development with strong production potential.

Herein, we evaluated Brazil's forest natural resources, providing information that could direct public policies regarding forest bioelectricity development in specific Brazilian territories to improve the energetic security and guide future forest waste exploitation.

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