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A Novel Methodology for Assessing the Electricity Generation Potential of Biomass Residues: A Case Study in the State of Minas Gerais, Brazil

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Abstract: This study presents a methodology for assessing the technical and economic potential of electricity generation from biomass residues, using thermochemical conversion technologies. Applied in the state of Minas Gerais, Brazil, the analysis focuses on residues from corn, soybean, coffee, eucalyptus, and sugarcane. A multi-criteria decision-making (MCDM) approach, integrated with GIS, was used to identify the most viable biomass sources and most suitable conversion technologies, namely the Rankine cycle, organic Rankine cycle, and gasification with internal combustion engines, based on Technological Readiness Levels (TRLs). Eucalyptus emerged as the most suitable residue due to its high energy density, while sugarcane residues were the most abundant. The economic feasibility analysis indicates levelized costs ranging from USD 0.10 to USD 0.24 per kWh, with the conventional Rankine cycle emerging as the most cost-effective option for plants with a capacity exceeding 5 MWe. The proposed methodology supports strategic bioenergy planning by integrating geospatial, technological, and economic factors.

Keywords: biomass; agricultural residues; bioenergy; MCDM; bioeconomy; GIS; power generation

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1. Introduction

The looming threats of climate change and air pollution underscore the urgent need for a global transition from fossil fuels. At COP28, a landmark decision committed humanity to phase out the use of fossil fuels "in energy systems in a fair, orderly and equitable manner within 25 years, accelerating the adoption of measures in this critical decade" [1,2]. Despite the consensus on the need for an energy transition, the pathways are not clearly stated, nor agreed upon. Key challenges include managing renewable energy variability, ensuring grid stability, developing energy storage solutions, and clarifying the role of nuclear energy [3]. In this context, biomass and bioenergy are pivotal within the energy–water–food nexus. Biomass, either in its natural state or converted into biofuels, can help mitigate the intermittency of wind and solar power, necessitating comprehensive assessments of land availability, water resources, geographic distribution, and biomass potential [4].

Bioenergy plays a fundamental role in the global energy matrix, currently accounting for around 10% of the primary energy supply, with an estimated production of 55.6 EJ. Projections indicate that its share of the primary energy supply could vary between 7.5% and 37% by 2050, depending on energy policies, technological advances, and the availability of land for growing biomass. Global bioenergy production could increase significantly, reaching between 64 EJ and 313 EJ, with the most optimistic scenarios suggesting an expansion of up to 21 times the current supply. This increase will be driven by the transition from traditional sources, such as firewood and agricultural waste, to high-yield energy crops and biological waste, converted using advanced technologies. Biomass can, thus, be consolidated as a viable alternative for the decarbonization of the energy sector, contributing to a more sustainable and diversified energy mix [5].

The growth of bioenergy on the global stage depends on several factors, including energy policies, technological advances, and the sustainable availability of biomass. Agricultural residues, forestry, and energy crops are becoming important sources for bioenergy production, and are helping to reduce fossil fuel dependence. However, challenges, such as competition for land use, its impact on biodiversity, and the need for more efficient technologies to convert biomass into energy, still limit its expansion. In order for bioenergy to play a central role in the global energy transition and reach the projection of producing up to 313 EJ in 2050, it is essential to invest in innovative solutions, such as advanced biofuels and integrated carbon capture and storage systems (CCUS). In addition, effective public policies and financial incentives can accelerate this transition, ensuring that bioenergy contributes to the decarbonization of the energy sector without compromising food and environmental security [6].

Recent publications from IRENA, UNIDO, and the ETC highlight biomass's role in future sustainable energy systems [7–9]. Studies by Colla et al., Kabeyi and Olanrewaju and Tun et al. emphasize practical biomass applications and the synergies with low-carbon hydrogen [10–12]. Biomass sources include agricultural waste, forestry residues, industrial byproducts, MSW, sewage, wastewater, and energy crops, like eucalyptus and algae [13]. The longstanding food/bioenergy dilemma, prominent since the 1980s, still influences contemporary discussions on land use [14,15].

Studies by da Cunha Dias et al. [5] and Errera et al. [6] highlight factors like food habits, waste, and land degradation that impact bioenergy cultivation. These papers forecast the availability of land and the technical potential of bioelectricity and biofuels in various scenarios in 2050 [5,6]. Biomass residues offer a solution that avoids using dedicated land for energy crops and aligns with circular economy principles [16]. Evaluating biomass energy potential involves theoretical, technical, economic, and sustainability considerations (Figure 1). Theoretical potential (Tp) estimates the raw energy content, while technical potential (Tecp) considers conversion efficiencies and logistics. Economic potential (Ecomp) assesses financial viability, and sustainable potential (Sp) considers ecological and food security constraints [17].

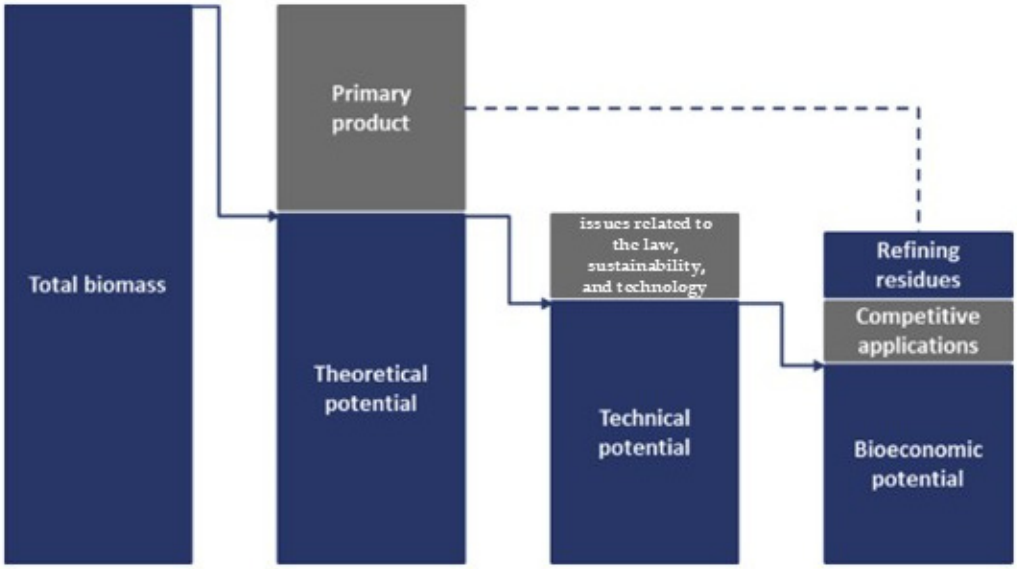

Figure 1. Stages in the assessment of biomass resource potential [18].

A holistic approach to the assessment of energy potential can unlock biomass's transformative potential in regard to a sustainable energy future. For this task, utilizing Geographic Information Systems (GIS) is fundamental in order to gain better knowledge and more effectively allocate biomass resources and design biomass energy systems. GIS visualize the spatial distribution and availability of biomass residues, aiding the resource allocation process [19]. GIS can be used to determine optimal plant sizing, positioning, and supply chain configurations, enhancing the efficiency of biomass power generation. GIS, combined with a multi-criteria decision-making (MCDM) approach, helps in choosing the best technologies and strategies for biomass energy deployment [20–22]. This synergy subsidizes the determination of the energy potential of biomass in a sustainable and scalable way.

Several publications have developed biomass and waste utilization methodologies, addressing spatial and temporal availability, logistics, and technology selection. Notable examples include the study by Gomez et al. (2010) that focused on a case study in Spain, a similar study by Lozano-Garcia et al. (2020) in Mexico, and the studies by Ji et al. (2023), and Ukoba et al. (2023) in Nigeria [23–26]. However, these studies primarily focus on the theoretical and technical potential of biomass, often using a single conversion technology, typically the conventional steam cycle, while overlooking aspects including biomass technology compatibility, logistical constraints, and economic feasibility. Addressing these gaps is essential for advancing biomass energy assessments and supporting sustainable energy systems.

Therefore, this study proposes a logical and sequential methodology for assessing the theoretical, technical, and economic potential of electricity generated from agricultural residues. The main novelty of this research lies in its integrated approach, which combines a multi-Criteria decision-making (MCDM) approach, specifically the Analytic Hierarchy Process (AHP), with georeferencing, and a selection procedure involving multiple thermochemical conversion technologies. Unlike previous studies that analyze these aspects separately, our approach systematically evaluates the most suitable biomass residues, estimates the energy potential at different levels, and calculates the levelized cost of electricity (LCOE) for mature technologies.

This paper introduces several key innovations: (i) a structured methodology for assessing biomass residues for electricity generation, considering not only the theoretical, but also the technical and economic constraints; (ii) a comparative analysis of different thermochemical technologies is conducted, including the conventional Rankine cycle, organic Rankine

cycle, and internal combustion engines coupled with gasifiers; (iii) the development of a method for determining the economic transportation radius of biomass residues; and (iv) the development of an integrated decision-support framework to optimize biomass energy planning in regions with a high level of agricultural activity.

This study provides strategic insights for optimizing agricultural waste management for electricity generation, by advancing biomass utilization planning through the use of a holistic, decision-oriented methodology. The application to Minas Gerais, an agriculturally dominant region with well-developed logistics infrastructure, further demonstrates its practical utility. This research supports the transition to cleaner, more resilient energy systems, aligning with global environmental and climate goals.

2. Materials and Methods

The primary objective of this study is to develop and apply a comprehensive methodology for assessing the technical and economic potential of electricity generation from diverse agricultural residues, incorporating the multi-criteria decision-making (MCDM) method, more specifically the Analytic Hierarchy Process (AHP), as well as georeferencing techniques, and the selection of the most suitable technology from among various thermochemical conversion technologies. The MCDM methodology is a set of methods used to evaluate and prioritize different alternatives based on multiple, often conflicting, criteria [27]. In this study, the AHP is applied as a structured technique that assigns relative weights to criteria through the use of pairwise comparisons, aiding in the selection of the most suitable biomass residues and conversion technologies [28]. Georeferencing is incorporated using Geographic Information Systems (GIS), which enables the spatial analysis of biomass availability and the assessment of logistical feasibility. Additionally, the levelized cost of electricity, LCOE, is used as a financial metric to compare the cost effectiveness of different biomass-based power generation systems [29].

The case study focusing on the state of Minas Gerais in Brazil is presented to illustrate the application of this approach. Key components of this methodology, as shown in the paper's graphical abstract, include the following:

- Utilization of the MCDM/AHP method to decide on the most suitable biomass residues for electricity generation across different microregions, considering multiple criteria and preferences;
- Determination of the theoretical, technical, and economic potential of biomass;
- Determination of the levelized cost of electricity (LCOE) for different mature technologies, providing insights into the economic viability and competitiveness of biomass-based electricity generation.

2.1. Structure of the Proposed Methodology

The utilization of the multi-criteria decision-making (MCDM) approach is essential in the context of this study for several compelling reasons. Firstly, the complexity inherent in evaluating diverse biomass agricultural residues for electricity generation requires a systematic and structured approach that can accommodate multiple criteria and preferences. MCDM provides a robust framework for the pairwise comparison of different criteria, such as technical feasibility, economic viability, environmental impact, and social acceptance, into a unified decision-making process [30]. By incorporating stakeholder preferences and expert judgments, MCDM enables a comprehensive and inclusive assessment that captures the multifaceted nature of energy planning and resource allocation. Moreover, MCDM facilitates the identification of trade-offs and synergies among competing alternatives, enabling decision makers to effectively consider complexities and uncertainties inherent to agricultural residue suitability utilization pathways [31]. In essence, the adoption of

MCDM ensures transparency, rigor, and objectivity in decision making, thereby enhancing the efficacy and credibility of strategic energy planning efforts to promote sustainable biomass utilization for electricity generation. In this context, Figure 2 presents a flowchart of the proposed methodology, divided into four stages: data gathering, modeling, decision making, and application.

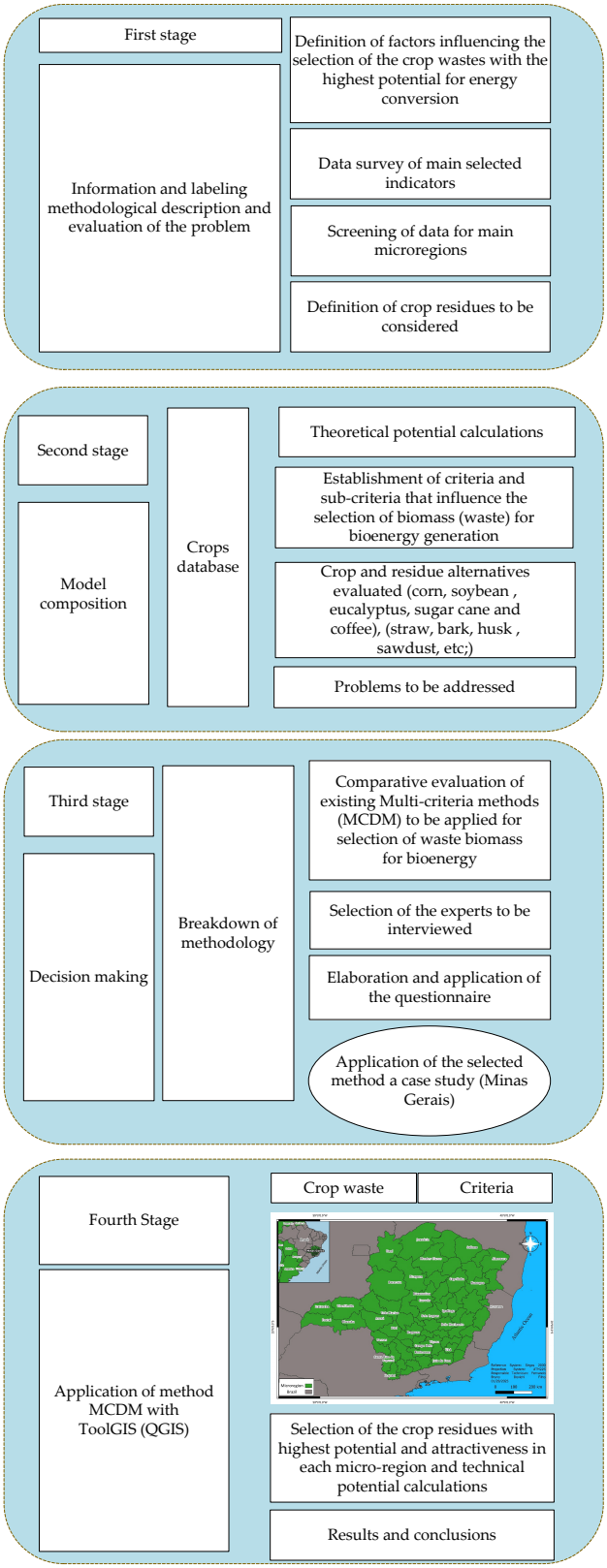

Figure 2. A flowchart of the proposed methodology [32].

These steps provide a methodical assessment of biomass residues for electricity generation by incorporating data collection, decision-making techniques, and spatial analysis tools.

The first stage refers to the identification of relevant biomass sources. The study began by assessing the primary crops in the target region, based on production volume and residue availability. This step was crucial for selecting biomass sources that accurately reflect the agrarian landscape. In the case of Minas Gerais, Brazil, data were retrieved from SIDRA, the agricultural statistics database managed by the Brazilian Institute of Geography and Statistics (IBGE). To enhance data reliability, information from SIDRA was validated via expert consultations and supplementary literature, ensuring consistency with the agricultural conditions in the state.

The second stage refers to the definition of the analytical model. A review of multi-criteria decision-making (MCDM) methodologies applicable to energy planning was conducted, including AHP, ELECTRE, TOPSIS, VIKOR, MAUT, PROMETHEE, and MACBETH. The Analytic Hierarchy Process (AHP) was selected for use in this study, due to its effectiveness in handling complex decision scenarios and its successful use in previous biomass energy assessments. The theoretical and technical potential of biomass electricity generation were quantified, and the evaluation criteria and sub-criteria were established.

The third stage involves the implementation of the decision-making framework. The AHP methodology was structured to rank biomass residues based on key attributes, such as availability, energy potential, economic feasibility, and TRLs. A GIS was integrated into the decision-making framework to facilitate spatial analysis of the biomass distribution and identify the most suitable locations for energy generation.

The fourth stage concerns the application of the framework to the case study region. The developed methodology was applied to Minas Gerais, analyzing the theoretical, technical, and economic viability of biomass-based electricity generation. Suitable conversion technologies were selected, based on efficiency and feasibility criteria, including the Rankine cycle, organic Rankine cycle, and gasification with internal combustion engines. The final analysis mapped optimal agricultural residues-to-energy pathways, incorporating cost evaluations and logistical considerations to support decision making.

2.2. Multi-Criteria Methods

An Analytic Hierarchy Process assessment, coupled with a GIS, was conducted to identify and select the biomass residues from the primary crops with the highest electricity production potential in a specific region (Figure 3) Table 1 shows the description of the AHP criteria and sub-criteria.

Table 1. Description of the AHP criteria and sub-criteria [32].

Technical Criteria		
N°	**Initials**	**Criteria**
1	RPj [GW]	Theoretical potential that can be converted into electricity (power) considering the current conditions and constraints (like the conversion efficiency, for instance)
2	RPR [%]	The ratio between the mass of residues/mass of agricultural products resulting from harvesting
3	η [%]	Biomass energy conversion efficiency (technical potential/theoretical potential)
4	AF [%]	Annual availability factor of residues, representing the relative fraction of the year when the residue is available (many crops are not available during the entire year)
5	AR [%]	Waste recovery rate, determining the fraction of residues that can be recovered for energy generation (the remaining part is lost)

Table 1. *Cont.*

	Technical Criteria	
N°	**Initials**	**Criteria**
6	RT [km]	Collection, storage, loading, and transport distance of the biomass to the generation plant
		Economic Criteria
7	CET [BRL/km]	Cost of harvesting, storage, loading, and transportation of the biomass to the generation plant
		Environmental Criteria
8	CO_2 [%]	Percentage of carbon dioxide in the combustion flue gas
9	ESR [%]	Environmentally sustainable removal rate, which assumes that part of the biomass must remain in the growing area to regulate the ecosystem
		Social Criteria
10	GDP [USD]	Indicator that represents the overall economic product of a city, region, state, country, or group of nations
11	CUI [MW]	Power availability based on the biomass plants in operation in the region
12	Demand (MWh/year)	Electricity demand to satisfy all the loads in a region used by the unit to carry out its operations within a year
13	HDI	Indicator that reflects the degree of development of a given society in terms of education, health, and income

The expert evaluation survey ranked the technical criteria as the most significant, followed by social, environmental, and economic criteria.

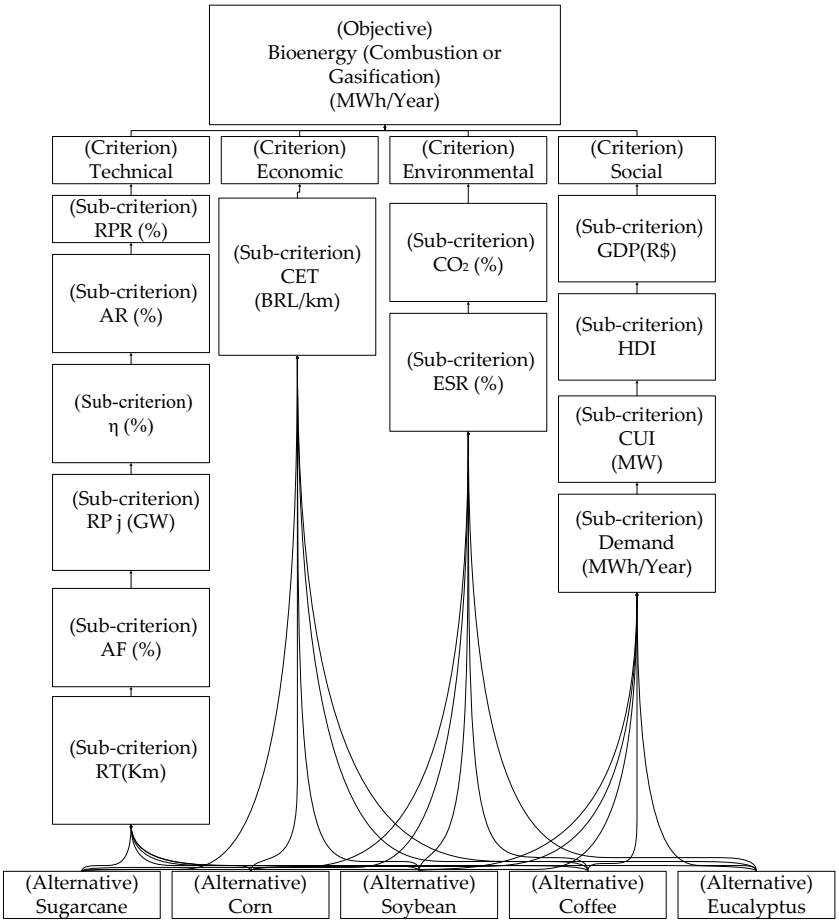

Figure 3. MCDM (AHP) method application flowchart, indicating criteria and sub-criteria [32].

2.3. Conversion Technologies: Technological Maturity

The types of biomass electricity generation technologies considered, along with the alternatives for biomass pretreatment technologies, thermochemical conversion routes, and energy carriers linked to the selected generation technology and its capacity, are shown in Figure 4. Their maturity levels were determined via a worldwide survey and subsequent statistical analysis, using the widely known TRL thermometer methodology as a reference. A questionnaire was made available through a weblink, collecting the judgments of 31 experts from several locations. Most respondents were from Brazil and Italy, followed by Spain and Colombia. Regarding the respondents' sector of work, the leading sector was universities, accounting for 86% of the total number of experts, followed by the industrial sector with 7%, and research institutions, also with 7%. The results from this survey were subjected to statistical consistency tests before their acceptance.

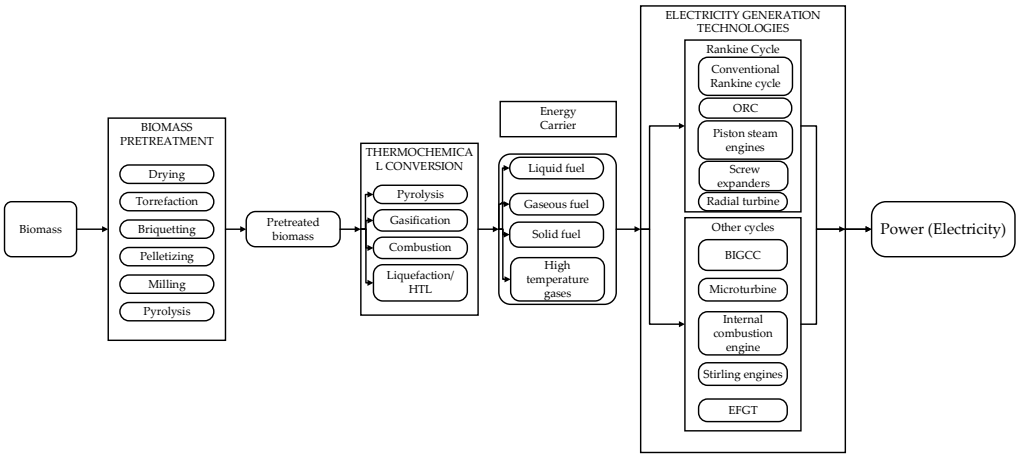

Figure 4. Main biomass electricity generation technologies, showing pretreatment technologies, thermochemical conversion routes, and energy carriers [33].

The data and results provided in this research facilitated a logical approach to selecting the technology with the highest current technological maturity (TRL) for the preliminary design of biomass electricity generation systems. Among the technologies surveyed, it is evident that the conventional Rankine cycle (CRC) technology is the most widely explored, disseminated, and commercialized globally, with the highest maturity level (predominant TRL 9). However, technologies such as the organic Rankine cycle (ORC) are expected to soon reach the highest maturity level, due to the hundreds of new facilities installed or planned worldwide [34].

Determining the TRL for gasifier–internal combustion engine (G/ICE) technology proved to be a complex task, as reflected in the survey results. The weighted TRL is 6, with individual survey responses ranging from 5 to 7. This variation is due to the different maturity levels of existing operational units, which have varying operational characteristics and reliability, depending on the manufacturer.

Finally, the technology for each evaluated case was selected among those with a TRL value corresponding to a high maturity level, specifically the conventional Rankine cycle (CRC), the organic Rankine cycle (ORC), and the gasifier/internal combustion engine system (G/ICE). The final technology selection for each microregion was based on efficiency vs. electric power curves, considering each evaluated technology's most widespread power application power range (left column in Figure 5). By superimposing these curves onto a single graph (right side in Figure 5) and the intersection with a vertical line corresponding to the thermal power of biomass makes it possible power , through successive approxima-

tions, to select the appropriate technology and determine its capacity and efficiency for a particular use case [33].

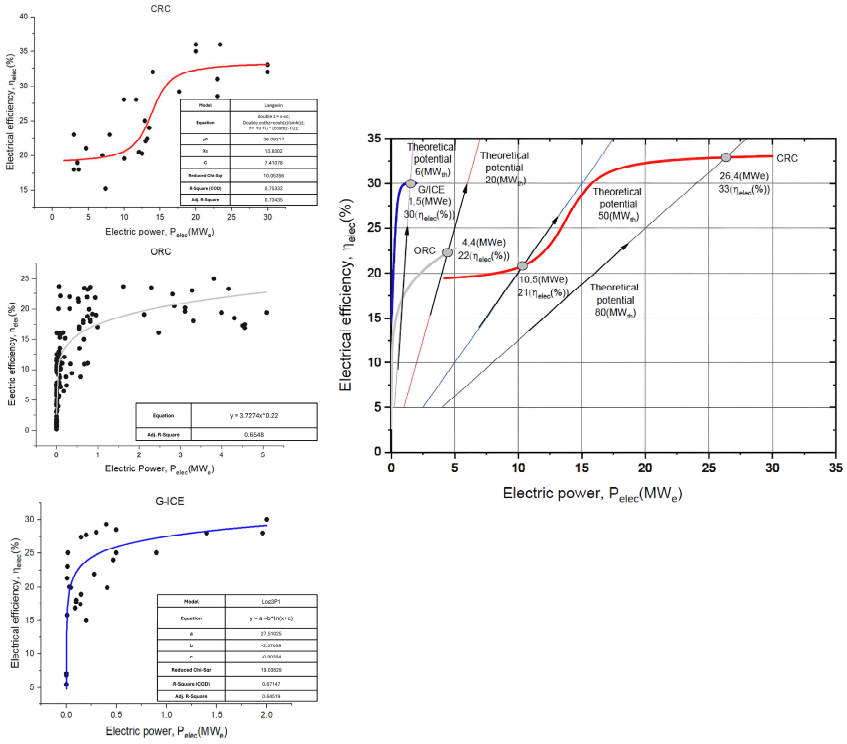

Figure 5. Fundamentals and visualization of the methodology for electricity generation technology selection, starting from biomass availability (adapted from Dovichi [34]).

The relationship between efficiency and installed power for different plants, based on CRC, ORC, and G-ICE technologies, was collected from scientific publications, resulting in the scatter plots shown on the left side of Figure 5. In general, efficiency increases with power, following a logarithmic regression curve. Otherwise, for CRC technology, the adjustment resulted in a Hill slope curve. In this case, three zones can be defined: the first with a power up to around 10 MWe, characterized by low steam parameters and efficiencies of around 20%; the second zone reaching about 20 MWe, where the steam parameters increase to 90–130 bar; and a third zone with efficiencies slightly above 30%, which includes modifications to the thermal scheme of the plant with the implementation of reheating and regenerative heating, in addition to parameters of up to 130 bar of pressure. Based on data on the availability of residual biomass for different case studies and its calorific value, it is possible to draw a straight line hypothetically showing the dependence between electrical capacity and efficiency for a given generation system. In Figure 5, three different lines were drawn as an example. The intersection of these lines with any of the efficiency vs. electric capacity curves allows us to define the bioelectricity technology to be used and to determine its power and efficiency; this approach is shown on the right side of Figure 5.

2.4. Logistics, Economic Radius, and Pretreatment

For the techno-economic modeling of the biomass residue supply chain, the study area is divided into microregions, and residue availability is considered. Each microregion was assumed to contain a single electricity generation plant located at its centroid, determined by the economical transportation radius for biomass residues.

In this model, each microregion was modelled to operate using a single biomass type, prioritizing the residue with the highest potential. The selected biomass is transported

to the central generation unit, wherein it undergoes pretreatment and energy conversion, according to the adopted technology.

The bioenergy supply chain has four stages: (1) residue collection, (2) handling, and transportation, (3) pretreatment, and (4) energy conversion. Only drying and crushing were considered as pretreatment steps. Pelletization was excluded due to its higher costs and logistical complexity. The pretreatment model balanced the trade-off between natural drying with a larger storage capacity and forced drying with more robust equipment.

Regarding logistics, biomass handling and transportation were treated as a single step. Handling includes loading, unloading, and material movement inside the power plant, while transportation covers moving residues from collection sites to generation plants. Pretreatment occurs at the generation unit to avoid additional transportation costs or the need for multiple smaller pretreatment facilities at collection sites. The economic transportation radius guided this decision. Figure 6 illustrates the entire logistics process, from residue collection to energy conversion.

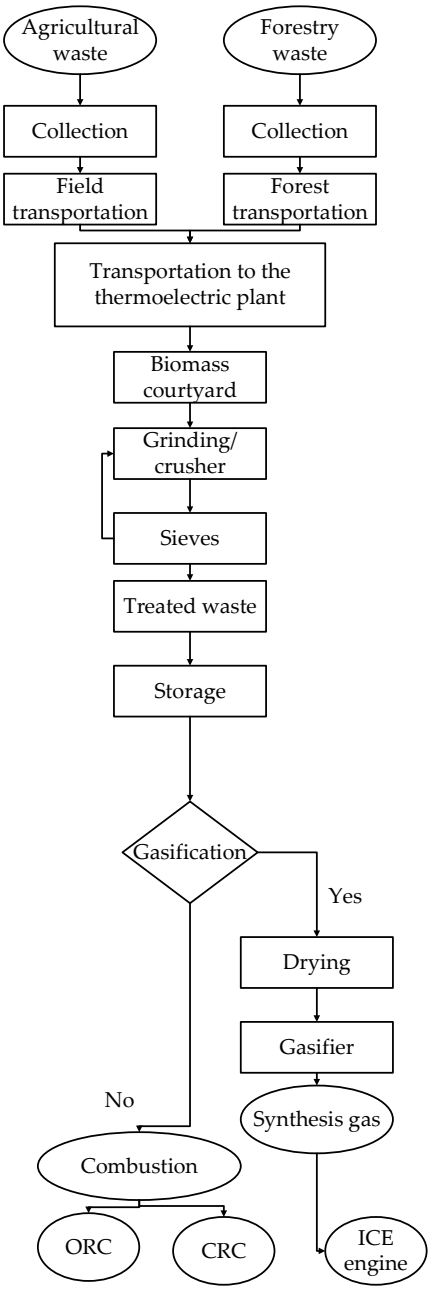

Figure 6. Harvest, transport, and pretreatment logistics.

Dovichi et al. highlight the impact of logistics costs on the levelized cost of electricity (LCOE) for two microregions. Expenses related to harvesting, transportation, crushing, and drying represented 25% to 38% of the LCOE, emphasizing the need for careful planning [34].

The pretreatment processes of crushing and drying consider the requirements of each selected technology and the type of combustion or gasification reactor employed (fixed, bubbling, or circulating fluidized bed). These processes were adjusted based on the biomass moisture content and size distribution [34].

3. Results: The Case Study of the State of Minas Gerais in Brazil

Minas Gerais (MG) is located in Brazil's southwest region (Figure 7). Its territorial area is 586,514 km^2, with an estimated population of 21,411,923 inhabitants. It was chosen due to its vast agricultural lands, advanced farming techniques, variety of crops, and high production of biomass residues. Additionally, its well-developed transportation infrastructure facilitates the logistics of biomass collection and energy distribution, making it an ideal case study for evaluating biomass-to-electricity potential. This state is the second largest agricultural producer in the country, with a high level of participation in the production of corn, beans, and coffee, among others. In 2020, the state had a record level of production of about 15.4 million tons of grain (an increase of 5.8% compared to the previous harvest, with a 4.7% increase in productivity).



Figure 7. Geographical location of the state of Minas Gerais.

According to the information available in the SIGA database (Information System for Generation of ANEEL, the regulatory agency for the electrical sector in Brazil), the state of Minas Gerais has 826 operational electricity generation plants, totaling 20.9 GW of installed capacity [35]. Most of this capacity comes from hydroelectric power plants, accounting for 64.6% of the state's installed capacity. Minas Gerais hosts 442 thermal-based generation units (both fossil and biomass), comprising 2.9 GW of installed capacity, constituting 14% of the state's total capacity. Explicitly focusing on biomass, there are 78 operational thermal power plants, with a total installed capacity of 1.96 GW. Additionally, the state has

seven authorized projects, two already under construction, collectively adding 0.2 GW of installed capacity.

The most representative residues considered in this study come from eucalyptus, soybean, sugarcane, and coffee crops, as determined through the use of Pareto analysis and an MCDM study. The QGIS 3.34.3 software was used for georeferencing the obtained data, which was sourced from IBGE SIDRA [36]. The application of the AHP method identified eucalyptus residues as the most suitable and viable biomass for electricity generation in most microregions in Minas Gerais, followed by residues from sugarcane, corn, and soybean.

3.1. Theoretical Potential

Once the biomass residue with the most significant potential and viability has been defined using the AHP method (Figure 8), its theoretical energy potential is determined, as shown in Figure 9. Selected power generation technologies and resulting technical potential by microregion are shown in Figures 10 and 11 respectively.

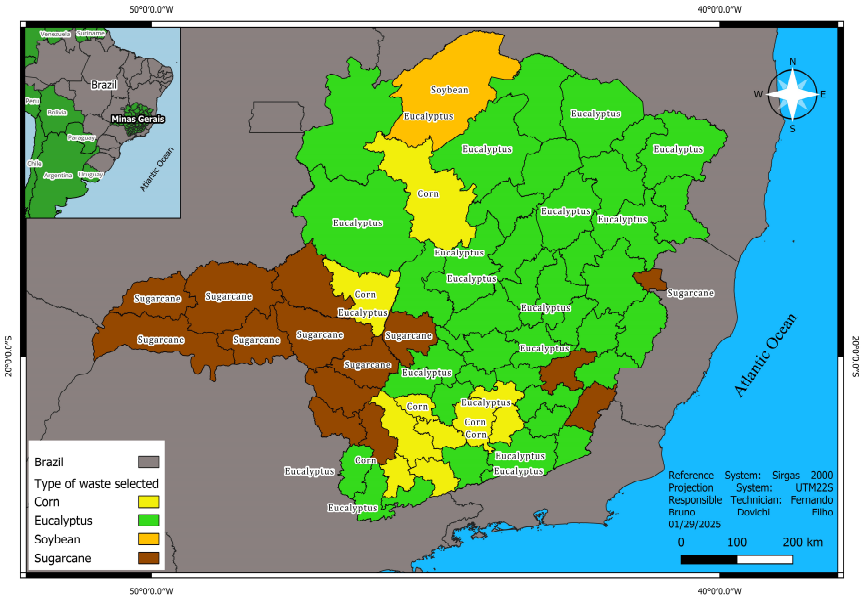

Figure 8. Biomass residues with the greatest potential and availability per microregion.

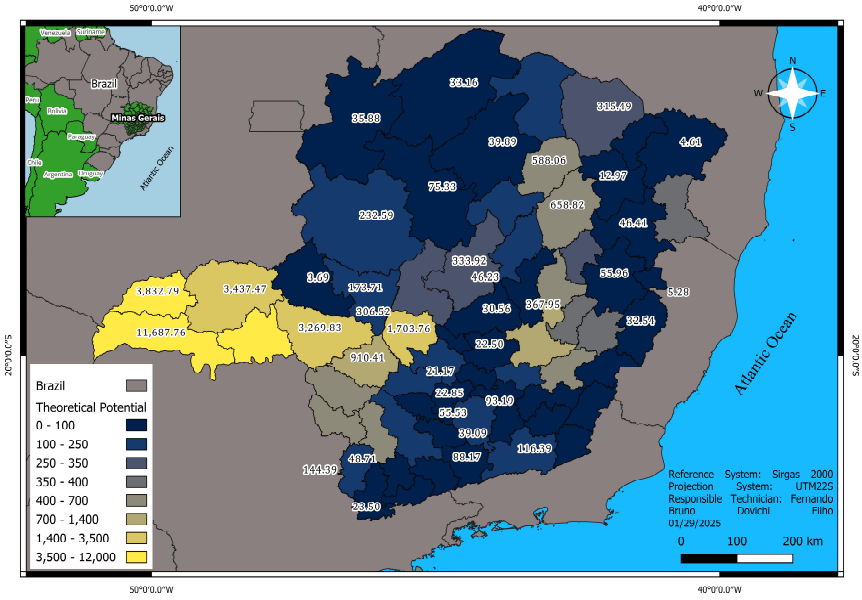

Figure 9. Theoretical potential of selected residues by microregion, in MW.

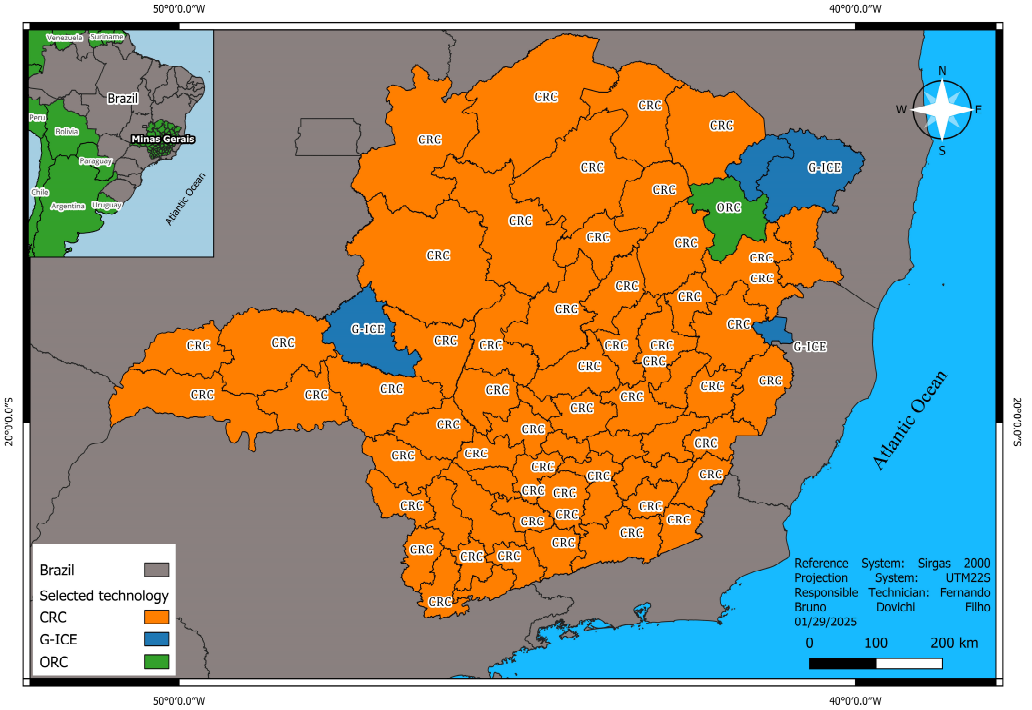

Figure 10. The results on the selection of feasible electricity generation technologies for each microregion.

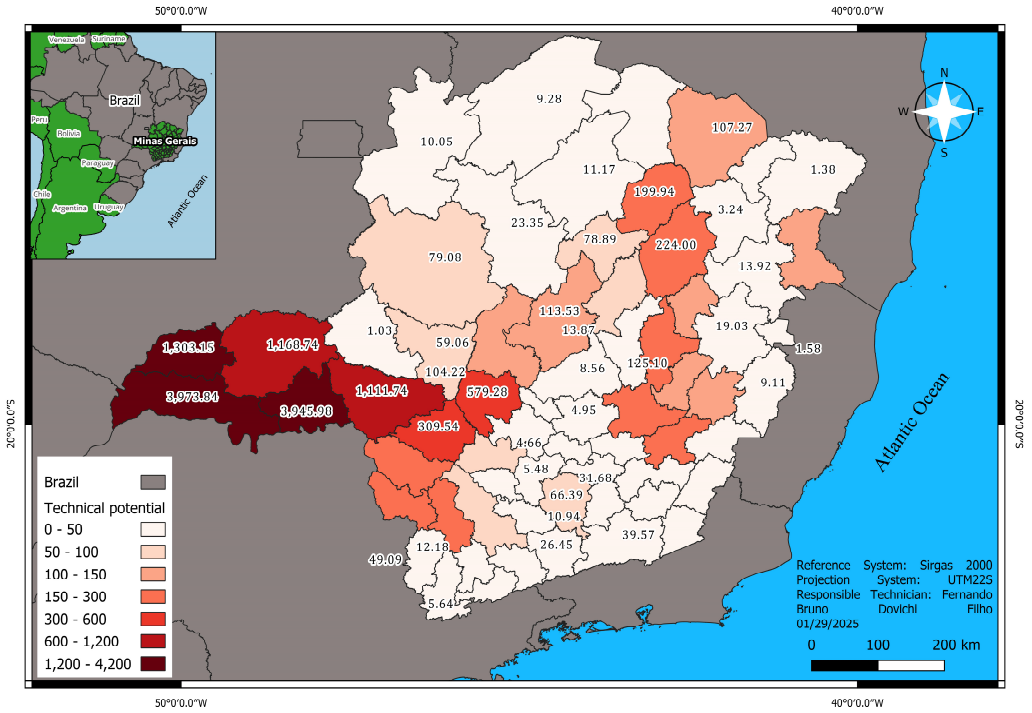

Figure 11. Technical potential of the selected residue by microregion, in MW.

3.2. Economic Potential

A techno-economic evaluation of the selected projects for electricity generation from biomass was carried out for each microregion, which resulted in power capacities ranging from 0.5 MW to 35 MW. The thermal efficiencies of these technologies ranged from 12% to 35%.

Table 2 presents the results of the economic feasibility study, using the following economic indicators: net present value (NPV), internal rate of return (IRR), levelized cost of electricity (LCOE), and payback time (PBT). These indicators allow us to determine

whether a project is economically viable. Figure 12 displays data on the levelized cost of electricity for each microregion.

Table 2. The results of the economic viability study of the bioenergy projects in each of the considered microregions.

Microregion	Crop	NPV [USD]	IRR [%]	PBT [Year]	LCOE [USD/kWh]	Project
Unai	Eucalyptus	7,437,825.89	12.49%	17.37	0.1336	Viable
Paracatu	Eucalyptus	77,359,713.31	2.94%	0.00	0.1538	Unviable
Januaria	Soybean	9,207,938.27	12.99%	16.21	0.1015	Viable
Janauba	Eucalyptus	18,603,349.06	11.77%	19.36	0.1078	Viable
Salinas	Eucalyptus	66,255,649.56	4.19%	0.00	0.1485	Unviable
Pirapora	Corn	14,544,687.43	12.30%	17.84	0.1053	Viable
Montes Claros	Eucalyptus	6,527,299.21	12.27%	17.91	0.1061	Viable
Grao Mogol	Eucalyptus	108,003,858.17	−1.34%	0.00	0.1686	Unviable
Bocaiuva	Eucalyptus	19,219,173.32	8.68%	0.00	0.1259	Unviable
Diamantina	Eucalyptus	5,052,681.92	9.88%	0.00	0.1191	Unviable
Capelinha	Eucalyptus	125,648,851.92	−5.07%	0.00	0.1770	Unviable
Araçuai	Eucalyptus	9,661,364.51	5.00%	0.00	0.1553	Unviable
Pedra Azul	Eucalyptus	4,948,844.60	−3.51%	0.00	0.2488	Unviable
Almenara	Eucalyptus	18,135,956.06	−3.77%	0.00	0.2616	Unviable
Teofilo Otoni	Eucalyptus	4,437,065.98	11.40%	20.62	0.1108	Viable
Nanuque	Eucalyptus	24,759,728.31	12.25%	17.97	0.1048	Viable
Ituiutaba	Sugarcane	980,457.22	10.37%	25.51	0.1162	Viable
Uberlandia	Sugarcane	12,248,156.92	9.28%	0.00	0.1226	Unviable
Patrocinio	Sugarcane	7,773,476.44	−2.02%	0.00	0.2408	Unviable
Patos de Minas	Corn	679,358.32	10.35%	25.65	0.1165	Viable
Frutal	Sugarcane	120,490,787.83	−4.49%	0.00	0.1747	Unviable
Uberaba	Sugarcane	1,591,017.22	10.42%	25.18	0.1160	Viable
Araxa	Sugarcane	32,432,066.05	12.90%	16.42	0.1012	Viable
Tres Marias	Eucalyptus	9,742,070.66	11.09%	21.83	0.1121	Viable
Curvelo	Eucalyptus	13,133,616.68	11.37%	20.75	0.1105	Viable
Bom Despacho	Sugarcane	10,074,771.11	11.12%	21.72	0.1120	Viable
Sete Lagoas	Eucalyptus	12,849,302.32	14.07%	14.24	0.0955	Viable
Conceição do Mato Dentro	Eucalyptus	9,519,391.70	12.51%	17.32	0.1034	Viable
Para de Minas	Eucalyptus	4,104,571.52	12.58%	17.14	0.1030	Viable
Belo Horizonte	Eucalyptus	5,037,485.63	12.65%	16.98	0.1027	Viable
Itabira	Eucalyptus	105,517,954.09	−1.35%	0.00	0.1675	Unviable
Itaguara	Eucalyptus	9,280,452.31	5.22%	0.00	0.1429	Unviable
Ouro Preto	Eucalyptus	28,052,551.66	12.56%	17.20	0.1033	Viable
Conselheiro Lafaiete	Corn	11,494,778.60	18.01%	9.97	0.0791	Viable
Guanhães	Eucalyptus	89,966,522.70	1.07%	0.00	0.1600	Unviable
Peçanha	Eucalyptus	28,697,060.25	7.79%	0.00	0.1306	Unviable
Governador Valadares	Eucalyptus	26,963,755.79	12.47%	17.41	0.1039	Viable
Mantena	Sugarcane	17,363,339.40	−3.09%	0.00	0.2553	Unviable

Table 2. *Cont.*

Microregion	Crop	NPV [USD]	IRR [%]	PBT [Year]	LCOE [USD/kWh]	Project
Ipatinga	Eucalyptus	23,580,730.89	8.25%	0.00	0.1281	Unviable
Caratinga	Eucalyptus	26,809,372.73	7.96%	0.00	0.1297	Unviable
Aimores	Eucalyptus	2,903,879.09	11.11%	21.74	0.1119	Viable
Piui	Sugarcane	21,878,581.13	12.23%	18.02	0.1053	Viable
Divinopolis	Eucalyptus	10,493,668.08	11.15%	21.58	0.1118	Viable
Formiga	Eucalyptus	13,122,576.11	7.63%	0.00	0.1315	Unviable
Campo Belo	Corn	2,001,396.87	11.09%	21.83	0.1119	Viable
Oliveira	Eucalyptus	2,001,396.87	11.09%	21.83	0.1119	Viable
Passos	Sugarcane	30,583,576.84	12.75%	16.74	0.1021	Viable
São Sebastião do Paraiso	Sugarcane	31,289,966.27	12.81%	16.61	0.1018	Viable
Alfenas	Sugarcane	33,807,841.16	13.00%	16.19	0.1006	Viable
Varginha	Corn	15,615,930.69	11.57%	20.03	0.1093	Viable
Poços de Caldas	Eucalyptus	7,701,931.64	10.93%	22.56	0.1131	Viable
Pouso Alegre	Eucalyptus	18,802,522.99	12.07%	18.47	0.1063	Viable
Santa Rita do Sapucai	Corn	11,996,811.80	12.40%	17.59	0.1042	Viable
São Lourenço	Corn	12,275,721.92	12.45%	17.47	0.1039	Viable
Andrelandia	Eucalyptus	19,688,511.99	12.15%	18.24	0.1058	Viable
Itajuba	Eucalyptus	1,725,390.43	11.10%	21.82	0.1118	Viable
Lavras	Corn	20,970,237.49	12.27%	17.92	0.1051	Viable
São João Del Rei	Corn	14,532,616.12	11.48%	20.34	0.1098	Viable
Barbacena	Corn	9,189,490.80	12.99%	16.22	0.1016	Viable
Ponte Nova	Sugarcane	46,124,899.48	14.14%	14.12	0.0949	Viable
Manhuaçu	Eucalyptus	12,120,010.05	12.68%	16.90	0.1034	Viable
Viçosa	Eucalyptus	25,697,116.37	12.38%	17.65	0.1045	Viable
Muriae	Sugarcane	3,688,049.54	8.92%	0.00	0.1245	Unviable
Uba	Eucalyptus	6,240,611.51	11.77%	19.37	0.1080	Viable
Juiz de Fora	Eucalyptus	21,068,172.22	12.01%	18.65	0.1067	Viable
Cataguases	Eucalyptus	12,139,609.59	11.94%	18.85	0.1071	Viable

Data from Table 2 and Figure 12 allows one to identify which bioelectricity projects are economically viable (green cells) and unviable (red cells) in a given microregion, as shown in Figure 13. This analysis allowed for the calculation of the state's economic potential, considering the data on bioelectricity projects that proved to be economically feasible. Figure 14 illustrates the total theoretical, technical, and economic potential of the state of Minas Gerais.

Additionally, it is important to acknowledge that market factors, such as fluctuations in biomass prices, changes in electricity market prices, and policy incentives, can significantly impact the economic feasibility of biomass energy projects. A sensitivity analysis considering these factors would provide a more robust assessment of the related investment risks and profitability. Future studies should explore the implications of these dynamics on biomass electricity generation in Minas Gerais, helping refine strategies for long-term energy planning.

As shown in Figure 14, the actual installed bioelectricity power amounts to only 31.0% of the calculated economic potential and 17.8% of the technical potential of the microregions. These data suggest considerable potential for expanding installed bioenergy capacity in Minas Gerais, which could further increase through the simultaneous utilization of various residual biomass sources in each microregion.

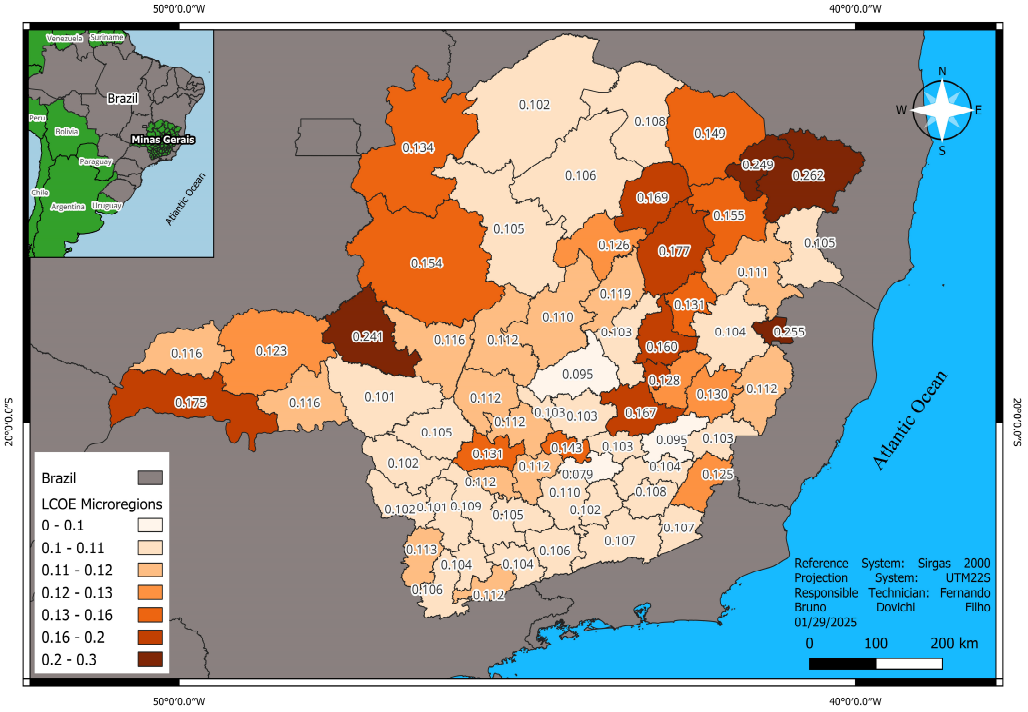

Figure 12. LCOE for the selected residue by microregion in the State of Minas Gerais, Brazil, in USD/kWh.

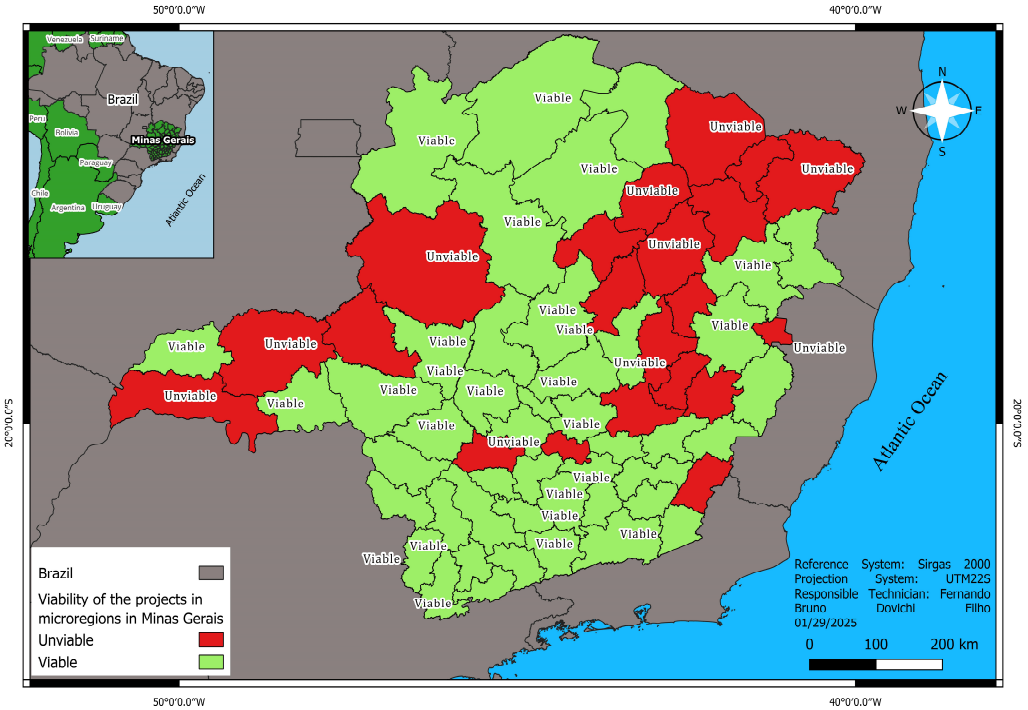

Figure 13. Map showing the economic viability of bioelectricity projects in the different microregions in the state of Minas Gerais, Brazil (viable and unviable).

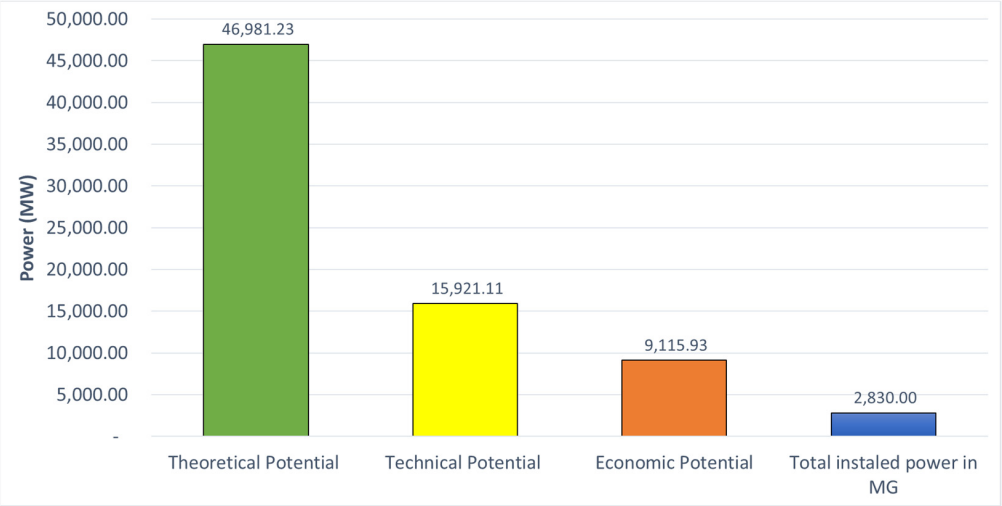

Figure 14. Biomass potential of the microregions in the state of Minas Gerais, Brazil.

4. Conclusions

According to the Brazilian Institute of Geography and Statistics (IBGE), the state of Minas Gerais is divided into 66 microregions. The AHP multi-criteria evaluation identified the most suitable biomass residues and mapped their theoretical, technical, and economic electricity generation potential. Eucalyptus, corn, soybean, coffee, and sugarcane residues were biomass sources considered to be energy resources.

The results revealed that eucalyptus is the most suitable biomass for electricity generation in 41 out of 66 microregions (62%), sugarcane in 14 microregions (21%), corn in 10 microregions (15%), and soybean in only 1 microregion (2%). Coffee residues were not selected as the most suitable biomass in any microregion due to their low availability. The prevalence of eucalyptus as the preferred biomass source is attributed to its extensive cultivation across Minas Gerais. Regarding its theoretical potential, Minas Gerais could generate approximately 47 GW from biomass residues. Eucalyptus residues have a theoretical potential of 7.3 MW (15% of the total), while sugarcane contributes the most with 38.8 MW (83%). Corn and soybean residues have a potential of 915 kW (2% of the total) and 33 kW (irrelevant), respectively. The high contribution of sugarcane is due to the large volume of residues, including straw, tops, and bagasse.

This study developed and demonstrated a comprehensive multi-criteria/GIS methodology for assessing the technical and economic potential of biomass electricity generation. The methodology included a survey of existing residues, ranking their availability, the multi-criteria selection of the most suitable biomasses, a georeferenced theoretical potential calculation, technology selection based on efficiency/power curves, and an economic potential calculation. The Rankine cycle emerged as the most appropriate technology for 61 microregions. The gasification cycle integrated with an internal combustion engine was chosen in four microregions, and the organic Rankine cycle was recommended for only one microregion. Economically viable plants had levelized energy costs of between USD 0.1012/kWh and USD 0.2408/kWh, with eucalyptus and the conventional Rankine cycle generally having the lowest costs.

The proposed methodology's main limitations are its consideration of only one type of biomass per microregion, that it ignores multi-residue conversion units, and the need for more detailed transportation logistics insights, including from GIS.

Integrating multiple biomass residues for energy generation offers potential benefits in regard to efficiency and resource utilization. However, practical challenges, such as varying physicochemical properties, logistical complexities, and the necessity for specific

pretreatment processes, render multi-residue approaches intricate. While Brazil has made significant strides in biomass energy production, particularly with sugarcane bagasse and eucalyptus residues, large-scale projects utilizing multiple agricultural biomass residues are not yet prevalent. Future research should focus on the feasibility of mixed biomass utilization, evaluating its effects on power generation efficiency, cost structures, and environmental performance to optimize biomass energy strategies.

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Abbreviations

MCDM	Multi-criteria decision-making (Tomada de Decisão Multicritério)
TRLs	Technological Readiness Levels (Níveis de Prontidão Tecnológica)
GIS	Geographic Information Systems (Sistemas de Informação Geográfica)
MWe	Mega Watt elétrico
GIS-MCDM	Abordagem combinada de GIS e MCDM
LCOE	Levelized cost of electricity (Custo Nivelado de Eletricidade)
AHP	Analytic Hierarchy Process (Processo de Hierarquia Analítica)
NPV	Net Present Value (Valor Presente Líquido)
IRR	Internal Rate of Return (Taxa Interna de Retorno)
PBT	Payback Time (Tempo de Retorno do Investimento)
MSW	Municipal Solid Waste (Resíduos Sólidos Municipais)
ANEEL	Agência Nacional de Energia Elétrica (Brasil)
IBGE	Instituto Brasileiro de Geografia e Estatística
SIDRA	Sistema IBGE de Recuperação Automática
UNIDO	United Nations Industrial Development Organization (Organização das Nações Unidas para o Desenvolvimento Industrial)
IRENA	International Renewable Energy Agency (Agência Internacional de Energia Renovável)
ETC	Energy Transitions Commission (Comissão de Transições Energéticas)

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