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Energy Recovery of Gases from Charcoal Production: Potential, Available Technologies, Costs, Sustainability, and Its Contribution to the Energy Transition in Brazil

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Abstract

Minas Gerais is Brazil's largest charcoal producer, relying on carbonization kilns that release effluent gases and waste energy while generating environmental impacts. This work evaluates the electricity generation potential from these gases using different conversion technologies. A database-based assessment of charcoal production units, based on official institutional records, enabled estimating the energy potential for 2020 and projecting it to 2030. Three technologies were assessed: Steam Rankine Cycle, Organic Rankine Cycle, and Externally Fired Gas Turbine. For each one, efficiencies were calculated and applied to the surveyed producers, ranging from 5% to 24% for power capacities between 100 kW and 2000 kW. The highest energy generation potential, 1348 GWh/year, was obtained using the regenerative and superheated ORC with n-decane as the working fluid. In addition, an economic analysis was performed based on Brazilian electricity auction prices, together with a sensitivity analysis of key variables, including installed power, electricity price, minimum attractiveness rate, taxes, operating hours, and capital expenditure. The results demonstrate that current technical and economic conditions are unfavorable for implementing waste-heat-based power plants in Minas Gerais. Plants below 10 MW are especially unfeasible. A Life Cycle Assessment estimated emissions of 2437.7 kg CO_2eq per ton of charcoal. Sustainable measures such as eliminating native wood use, increasing Gravimetric Yield, and adding afterburners could reduce emissions by over 57%.

Keywords: slow pyrolysis gases; carbon footprint; organic Rankine cycle (ORC); steam Rankine cycle (SRC); externally fired gas turbine (EFGT)

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1. Introduction

Considering all production routes, the steel industry is responsible for 7 to 9% of global CO_2 emissions, with an average emissions intensity of 1.91 tCO_2 per tonne of crude steel. However, the BF-BOF (blast furnace/oxygen converter) route, widely used in Brazil, has a higher emissions intensity of 2.33 tCO_2 per tonne of steel [1]. This high carbon footprint is directly related to its high energy consumption, which varies between 19 and 23 GJ per ton of steel, due to the need for coke as a reducing agent in the blast furnace and the intense

use of heat in thermal processes [2]. After three years of decline, global steel demand is expected to grow again in 2025, with an increase of 1.2%, reaching 1772 Mt [3]. Given this recovery scenario and the need to reduce emissions, sustainable alternatives are essential for the global competitiveness of the steel industry.

Charcoal is a sustainable alternative to coal in the steel industry and has been widely discussed in the literature as a pathway to reduce the carbon intensity of ironmaking, particularly when associated with efficient carbonization processes and sustainably managed planted forests. With a production of 6.7 million tons, Brazil leads the global production of charcoal. Minas Gerais is the largest producer due to its large planted forest area, representing 63% of the eucalyptus plantations in the Southeast region. In the same period, 24% of the national pig iron production (7.6 Mt) used this renewable source [4].

Brazil ranks 9th in the global production ranking, with 32 million tons of crude steel in 2023, representing 1.7% of world production. The sector's installed capacity is 51 million tons per year, with Latin America accounting for 54.9% of production [5].

The Brazilian steel industry consumed 1.1 million tons of charcoal. At the same time, 8.6 million tons of mineral coal/anthracite and 6.7 million tons of coke were used [6], highlighting the significant potential for substitution and the need to increase the sustainability of the charcoal production sector.

However, the carbonization of biomass is still an inefficient process, wasting around 30% of the wood energy in the form of unused gases. In addition, the uncontrolled release of these gases contributes to adverse environmental and air-quality impacts. Similar challenges related to the energetic use of raw pyrolysis gases, such as variable composition, particulate matter, and tar formation, have also been reported in biomass pyrolysis and biochar production systems in Europe and North America, indicating that the recovery of low-quality carbonization gases is a global engineering challenge rather than a context-specific issue.

The controlled recovery and energetic use of carbonization gases represent a key pathway for the modernization of the charcoal production sector. Beyond increasing overall energy efficiency, such systems enable improved control of gaseous emissions, contributing to reduced local air pollution and improved environmental performance of carbonization units. From an economic perspective, the valorization of effluent gases through electricity generation can partially offset production costs, improving the competitiveness of charcoal-based ironmaking in Brazil, particularly in a context of rising energy prices and increasing pressure for cleaner production routes.

In this context, this study assesses the potential for generating electricity from effluent gases from charcoal production in Minas Gerais, analyzing different energy conversion technologies. For this purpose, three main technologies were considered: the Steam Rankine Cycle (SRC), the Organic Rankine Cycle (ORC), and the Externally Fired Gas Turbine (EFGT). The electric potential maps were generated from a survey of the carbonization industries in the sector in Minas Gerais. The study used data from different sources, including IBGE (Brazilian Geography and Statistics Institute), SISEMA (State System for the Environment and Water Resources of Minas Gerais), and PNLA (National Environmental Licensing Portal), to map the regions with the highest concentration of charcoal production. With this data, the volumes of effluent gases available for electricity generation were estimated. In addition to the technical and economic assessment, the study includes a spatial analysis of electricity generation potential, an inventory-based assessment of greenhouse gas (GHG) emissions associated with the evaluated systems, and a technological maturity discussion, aiming to support a preliminary evaluation of the feasibility of energy recovery from charcoal carbonization gases in Minas Gerais.

1.1. Main Innovations and Contributions

This work offers a detailed energy, economic, and environmental survey of the insertion of different electricity generation technologies for using waste gases from the wood carbonization process in Minas Gerais, Brazil. The main contributions include the following:

i. Identification of the main charcoal-producing regions in Minas Gerais, estimating the availability of effluent gases and their energy potential for electricity generation.
ii. Comparison of different energy conversion systems (SRC, ORC, and EFGT), considering efficiency, technological readiness level, and economic criteria.
iii. Study of the economic and financial aspects of the technologies, highlighting factors such as investment, operation, and financial return costs and their impact on the economic viability of the alternatives.
iv. Environmental Impact Analysis through Life Cycle Analysis and strategies for reducing the environmental impacts of carbonization.
v. Quantification of the conventional thermoelectric generation capacity that can be replaced by the energy use of wood carbonization gases in Brazil's energy transition context.

1.2. General Aspects

The charcoal production process in Brazil is both underdeveloped and inefficient. Renewable charcoal is produced from the slow pyrolysis of planted biomass, during which condensable and non-condensable gases are generated as by-products. These gases are released into the atmosphere, which not only degrades air quality but also results in the loss of a renewable energy source. These by-products account for approximately 25% of the initial energy contained in the wood [7–10].

Considering the importance of the carbonization process, Bustos-Vanegas et al. [11] were able to produce insights into the operation of the kilns and the temperature profile on the walls, besides establishing consistent initial conditions of temperature and heat flow for kinetic models by modeling a 700-m^3 industrial furnace and simulating the carbonization process through Computational Fluid Dynamics.

Sangsuk et al. [12] analyzed the conversion efficiency of barrel furnaces with a heat manifold to produce charcoal and biochar. The authors used tamarind wood and corn cob as biomass and obtained from 11 kg to 12 kg of charcoal with a moisture content of 5% for a 200 L oven. The tamarind wood coal had between 20% and 21% of volatile matter, from 68.7% to 69.8% of fixed carbon, 3.8% to 5.6% of ash, and LHV between 30 and 31 MJ/kg. The energy conversion efficiency of the barrel furnaces with a heat manifold was between 40% and 48%.

Tintner et al. [13] studied the temperature profile in a rectangular kiln through infrared spectroscopy and thermocouple measurements. The temperatures ranged from 400 °C to 700 °C. Elemental analyses were performed, and prediction models for carbon, hydrogen, and oxygen content based on the infrared spectrum were established, achieving very high coefficients of determination (above R = 0.93). The authors concluded that infrared spectroscopy can be used as the basis and standard technique for describing the characteristics of charcoal, since it was able to predict together the degree of pyrolysis and elemental analysis.

Studies related to the reuse of effluent gases from the wood carbonization process for the generation of electricity have gained notoriety. Cardona et al. [14] evaluated exhaust gases during the roasting of eucalyptus trees and found the presence of compounds such as CO_2, CO, toluene, acetic acid, furfural, among others. Such reactive compounds are harmful to workers and local communities, which reinforces the idea of the need for an appropriate destination for the effluent gases from the charcoal production process.

Moreover, Castro [15] states that several Brazilian coal producers are concerned about environmental restrictions related to pyrolysis gases and are investing in modernization to control emissions and benefit from their energy, including options such as wood drying, self-sustaining kilns, and electricity generation. In the latter case, these gases can be used to produce heat and energy in thermodynamic cycles such as ORC, Steam Cycles, SRC, or EFGT.

Leme et al. [9] studied the energy potential of charcoal production using the three technologies mentioned above. The energy recovery of gases from the carbonization of wood through its burning was assessed by using the heat generated to produce electricity. The authors concluded that such technologies could reduce CO_2 equivalent emissions while producing electricity.

In this sense, Vicente Leme et al. [16] assessed the synchronous use of industrial batch kilns, waste gas combustion, and energy recovery for electricity generation through Life Cycle Analysis (LCA). Their study found that integrating electricity production with charcoal manufacturing significantly reduces environmental impacts. Energy recovery demonstrates a high life cycle energy output/input ratio of 6.9 per year. Waste gas combustion and electricity generation decrease CO_2 equivalent emissions by 3050.6 kg per metric ton of charcoal produced. Furthermore, the principal impact category, Photochemical Oxidation, can be reduced by up to 90% through gas flaring. Alves e Silva et al. [17] evaluated the potential for improving the environmental sustainability of charcoal production through the utilization of by-products. They found that Photochemical Oxidation is the primary impact category, mainly driven by CO emissions from carbonization kilns. By harnessing by-products, it is possible to generate between 0.19 and 0.26 MWh of electricity per ton of charcoal, with the inclusion of forest residues and insoluble tar increasing this potential by 36%. Additionally, the use of charcoal by-products can offset greenhouse gas emissions by 14 to 203 kg per ton of charcoal. The adoption of Pyroligneous Extract is particularly beneficial, leading to a 6% reduction in GHG emissions and a 47% decrease in abiotic resource consumption.

Silva et al. [18] developed a system to quantify GHG emissions and carbon removals in carbonization processes while calculating economic viability indicators for forestry and charcoal production. The system's results promote the adoption of good practices in charcoal production, leading to cleaner techniques, environmental improvements, financial gains, and better working conditions. Although these studies provide valuable contributions regarding thermodynamic behavior, environmental impacts, and economic aspects of charcoal production and gas utilization, they are generally focused on specific processes, technologies, or isolated case studies. Consequently, they do not address, in an integrated manner, a state-wide assessment for Minas Gerais that simultaneously combines electricity generation potential, regional spatial mapping, comparative evaluation of conversion technologies, greenhouse gas emission inventories, economic performance, and technological maturity considerations to assess the readiness of these systems across different technological routes.

2. Methodology

A five-step methodology was employed to achieve the proposed goals and develop consistent results. In this sense, a flowchart of this work methodology was created, and it is presented in Figure 1.

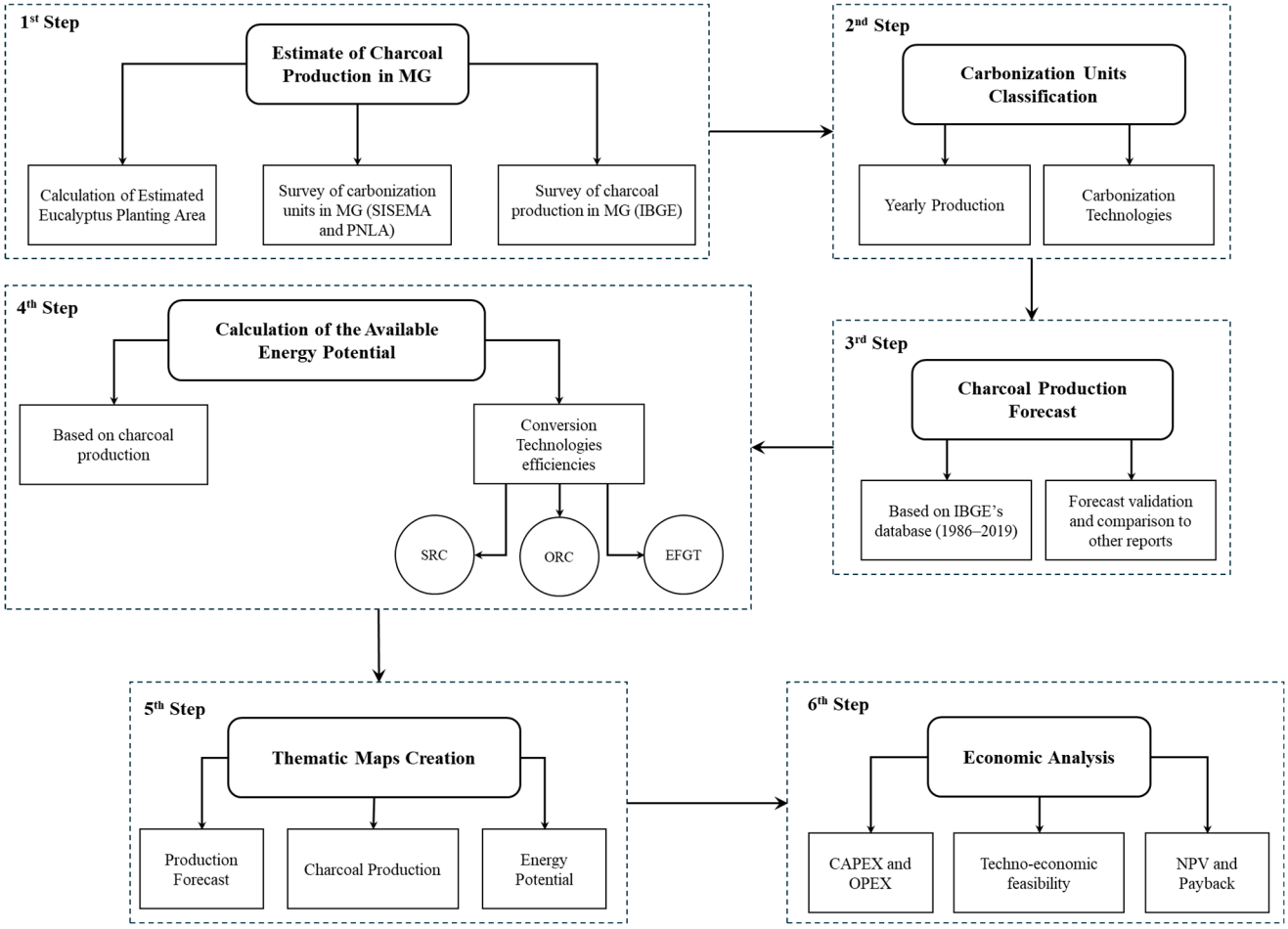


Figure 1. Methodology flowchart.

The first step is the Estimate of Charcoal Production in Minas Gerais, which was carried out using different databases: IBGE, SISEMA, and PNLA. The data from each of these three agencies are complementary, and then they were cross-checked to obtain a real estimate of the number of carbonization and charcoal production units in Minas Gerais.

The second step is the Classification of Charcoal Production Units (CHPUs), in which, with the available information on producers and productivity estimates, the CHPUs were classified in terms of production and carbonization technologies.

The third step is the Charcoal Production Forecast for Minas Gerais, which was made using an exponential smoothing function and validated using the last 10 years of available data and similar projections made in Minas Gerais.

The fourth step is the Calculation of the Available Energy Potential for the State based on the quantity of charcoal produced, the efficiency of the charcoal kilns, the volume of effluent gases in each unit, the average LHV, and the efficiencies of the conversion technologies adopted. Non-condensable gas (NCG) flow rates were estimated using mass and energy balance calculations within the thermodynamic models.

Following that, the results of production and energy potential were extrapolated, based on the forecast made previously, to the following years. Some scenarios were considered, ranging from the most optimistic to the most pessimistic regarding electricity generation. To better illustrate each result and established scenario, maps were created.

In the sixth step, the Economic Analysis was carried out, the cost of acquisition (CAPEX) and operation (OPEX), the sale price of energy, and payback for the viability of the projects were calculated.

Finally, the LCA aims to estimate the contributions to GHG emissions from charcoal production in Minas Gerais. The inventories and the system's evaluation were based on data collected from the literature, representing typical charcoal production in the state.

2.1. Step 1: Estimate of Charcoal Production in MG

2.1.1. Survey of Charcoal Production in MG

The IBGE Automatic Recovery System [19] could access information on the quantity of charcoal produced in Minas Gerais. Data were consulted in November 2020, and information related to charcoal production in MG from 1986 to 2019 is available.

The query considered "Table 291: Quantity produced and value of production in forestry, by type of forestry product". This table is part of the IBGE Automatic Recovery System [19] and contains information on the quantity of charcoal produced at the municipal level, from which the actual data were obtained, which served as the basis for calculations and comparisons in the following steps.

2.1.2. Survey of Charcoal Production Units in MG (SISEMA)

To obtain the number of CHPUs and better characterize the production in Minas Gerais, the State System for the Environment and Water Resources (SISEMA) was used. Based on this system, environmental licenses included in the G-03 listing of COPAM Brazilian Normative Deliberation No. 217 of 6 December 2017 [20], were sought. The G-03 listing was established by the Minas Gerais State Environmental Policy Council (COPAM—MG) and refers to licenses to produce charcoal in the State.

As a research criterion, the environmental licensing processes considered were the ones with licenses up to 10 years, which is the maximum period licensed in the State. Therefore, the projects that had the listings G-03-03-4 [20] (production of charcoal from planted forests) and G-03-04-2 [20] (production of charcoal from native origin) as the primary or secondary activity were searched.

2.1.3. National Environmental Licensing Portal (PNLA)

To verify the information collected from SISEMA, the National Environmental Licensing Portal (PNLA) was used as an additional source. In this portal, a survey of enterprises was carried out according to the National Classification of Economic Activities 2.1 (CNAE) [21].

The environmental licenses of the projects designated as 0220-9/02 (production of Vegetal Charcoal—native forests) and 0210-1/08 (production of Vegetal Charcoal—planted forests), according to the CNAE classification [21], with an expiration date from 31 December 2020 to 31 December 2030 were considered; this period refers to the 10-year limit of the license.

All current licenses found, whether with federal permits, granted by the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA), or State licenses, granted by the State Secretariat for the Environment and Sustainable Development (SEMAD), were considered in this work.

2.2. Step 2: Classification of Charcoal Production Units

As much of the information regarding the number and type of ovens was not explicit in the documents analyzed, an estimate was made of the kind of carbonization technology used by each producer. This was performed to set efficiency values for each production unit and, thus, estimate the mass flow and calorific value of waste gases available for electricity generation. In addition, the planted area of eucalyptus needed to supply the estimated charcoal production for 2020 was also calculated. Such a calculation was made based on average values of production efficiency and planted area for eucalyptus trees in Brazil. The survey did not explicitly distinguish multi-stage kiln configurations. The analysis is

based on kiln capacity, production scale, and carbonization technology, which were the consistently available parameters across the surveyed sites.

The eucalyptus planted area was calculated using Equation (1), which relates charcoal production to the average performance of the carbonization process and the main physical characteristics of eucalyptus biomass.

$$A_p = \frac{Q_c}{\eta_k} \times \frac{\rho_w}{m_t} \times A_t \quad (1)$$

where

A_p is the estimated eucalyptus planted area $[m^2]$;
Q_c is the charcoal production volume $[m^3]$;
η_k is the average gravimetric efficiency of the carbonization kilns $[-]$;
ρ_w is the average bulk density of eucalyptus wood at 50% moisture content [$kg \cdot m^{-3}$];
m_t is the average mass of an individual eucalyptus tree [kg];
A_t is the average planting area per tree $[m^2]$.

The numerical values adopted for the parameters in Equation (1) are summarized in Table 1.

Table 1. Parameters adopted for estimating the eucalyptus planted area [22].

Parameter	Symbol	Value	Unit
Wood density (50% moisture)		720	$kg \cdot m^{-3}$
Average tree mass	m_t	500	kg
Average planting area per tree	A_t	6	m^2

Moreover, most of the licenses found did not contain information on the type of carbonization technology used by the projects. Therefore, some types of technology were attributed to the CHPUs based on the data of charcoal production per furnace in each unit. As an attribution criterion, the kiln type, average coal production, and production efficiency values were taken from the study by Rodrigues and Braghini Junior [23]. The values considered are summarized in Table 2.

Table 2. Characteristics of the kilns considered in this study [23].

Kiln Type	Coal Production [MDC]	Gravimetric Yield [%]
Hot tail	192–240	25–30
Surface kiln	246–336	30–35
Polikor kiln	257	25–35
Slope kiln	288	25–35
Hive kiln	600–720	27–35
Argentine kiln	848–942	27–35
VMR kiln	1132	27–33
Rectangular brick kiln	1512–4560	34–40
Metal kiln	2174–2478	34–40
Continuous retort	7246–36,232	33
French CML kiln	9058	20–25

2.3. Step 3: Charcoal Production Forecast for MG

For the charcoal production forecast in Minas Gerais, the IBGE database was used, considering the data from 1986 to 2019. The accumulated production of the municipalities for each year was arranged in ascending order, and the function "FORECAST.ETS" from Microsoft Excel® was used.

To validate the function, production values from 2009 to 2019 were predicted and compared with real values. Therefore, it was possible to calculate the average relative error for a 10-year forecast based on the available data history.

In addition, a comparison of the calculated values and the values of the forecast carried out by the Superintendency of Supply and Agricultural Economy was also made. By this, it was possible to compare the relative errors of the estimates of the present study and the one previously mentioned.

2.4. Step 4: Available Energy Potential in the State

To calculate the energy potential in MG, various scenarios dependent on charcoal production and conversion technologies are considered.

2.4.1. Electricity Generation Technologies Considered in the Selection

The selection of CRC, ORC, and EFGT is based on technological maturity (TRL 7–9), efficiency, and economic criteria. CRC is widely commercialized (TRL 8–9), reaching 25–36% efficiencies. ORC is indicated for small and medium scales, with TRL 7–9 and 15–25% efficiencies. EFGT, although emerging (TRL 6–7), has the potential for decentralized applications and the use of carbonization gases [24,25].

2.4.2. Thermodynamic Simulation Models and Performance Indicators

The thermodynamic models developed considered the generation of electricity using SRC, ORC, and EFGT Cycles within the range of 100 to 2000 kWel, and average LHV of waste gases of 1579 kJ/kg were contemplated. The average LHV was obtained from measurements performed in the Technical Report n°. 4 [26].

To ensure transparency, reproducibility, and accessibility of the thermodynamic modeling backbone, the main design assumptions and performance-related parameters adopted for each power generation technology are explicitly summarized below. These parameters define the operating conditions, efficiency assumptions, and boundary conditions applied in the simulations and constitute the core inputs of the SRC, ORC, and EFGT models.

For the Steam Rankine Cycle (SRC), the simulations were performed considering typical industrial operating conditions for waste gas and waste heat recovery systems applied to charcoal carbonization plants. The adopted parameters include ambient reference conditions, boiler pressure and steam temperature levels, isentropic efficiencies of turbines and pumps, condensation pressure, and auxiliary electricity consumption. These assumptions reflect practical design constraints and operating conditions for SRC applications using low-calorific waste gases. The values obtained from the thermodynamic models developed for the SRC are presented in Table 3.

Table 3. Assumed parameters for the SRC system mass and energy balances.

Parameter	Value	Unit
Ambient temperature	25	°C
Ambient pressure	101.325	kPa
Turbine isentropic efficiency	50–75	%
Fuel LHV	1158–2000	kJ/kg
Pump isentropic efficiency	70	%
Steam temperature	300–320	°C
Boiler pressure	2000	kPa
Condensation pressure	10–50	kPa
Deaerator pressure	Badr	kPa
Auxiliary equipment electricity consumption	5% of gross power	–

For the Organic Rankine Cycle (ORC), the thermodynamic model was based on steady-state mass and energy balances considering a high-temperature waste gas source. The main parameters include assumed isentropic efficiencies for the turbine and pump, pinch-point temperature differences in the evaporator and condenser, condensation temperature, superheating and subcooling temperature margins, and reference temperatures of the hot and cold sources. These assumptions are consistent with standard ORC design practices for low- to medium-temperature heat recovery applications. The adopted parameters and modeling assumptions for the ORC system are summarized in Table 4.

Table 4. Assumed parameters for the ORC system mass and energy balances.

Parameter	Value	Unit
Pump isentropic efficiency (η_B)	60	%
Turbine isentropic efficiency (η_T)	80	%
Evaporation pinch point (ΔT_{PPevap})	6	°C
Condensation pinch point (ΔT_{PPcond})	10	°C
Condensation temperature	47	°C
Hot source temperature	350	°C
Cold source temperature	25	°C
Carbonization gas mass flow rate	1.0	kg/s
Superheating temperature difference	5	°C
Subcooling temperature difference	3	°C

The Externally Fired Gas Turbine (EFGT) model was evaluated at its nominal design point under ISO reference conditions [27]. The adopted parameters describe the thermodynamic state of the working air throughout the compression, external heating, and expansion stages, as well as the main performance characteristics of the compressor, turbine, heat exchanger, and generator. These inputs are representative of small-scale externally fired gas turbine systems operating with low-heating-value waste gases. The main design and performance parameters adopted for the EFGT simulations are presented in Table 5.

Table 5. Nominal design parameters adopted for the Externally Fired Gas Turbine (EFGT).

Parameter	Value	Unit
Net electrical power	99.8	kW
Turbine mechanical power	268.0	kW
Compressor mechanical power	162.0	kW
Electrical efficiency (ISO 3977-2 reference conditions [27])	16.7	%
Fuel inlet temperature	60	°C
Air temperature at compressor outlet	214	°C
Air temperature at turbine inlet	850	°C
Air temperature at turbine outlet	557	°C
Air mass flow rate	0.80	kg/s
Fuel mass flow rate	0.07	kg/s
Combustion gases mass flow rate	0.87	kg/s
Exhaust gas temperature	329	°C
Pressure ratio	4.5	–
Compressor isentropic efficiency	78	%
Turbine isentropic efficiency	83	%
Heat exchanger area	164	m^2
Heat exchanger volume	1.32	m^3
Generator efficiency	98.5	%

The EFGT model was evaluated at its design point under ISO reference conditions (ambient temperature 15 °C, atmospheric pressure 101.32 kPa, relative humidity 60%) [27], based on the model proposed by Kautz and Hansen [28], assuming steady-state operation.

The values obtained from the thermodynamic models developed for the SRC are presented in Table 6. The main parameters considered were the efficiency and consumption of non-condensable gases (NCGs).

Table 6. Values obtained from thermodynamic models for the SRC.

SRC				
Efficiency	10.4%	12.5%	13.6%	14.6%
Power [kW]	500	1000	1500	2000
Gas consumption [kg/s]	4.14	6.89	9.53	11.80

For the Steam Rankine Cycle (SRC), a sensitivity analysis was performed to assess the influence of the lower heating value (LHV) of the non-condensable gases on system performance. As expected for Rankine-based power cycles, the SRC exhibits a strong dependence on fuel energetic quality, since the available thermal input directly affects steam generation conditions and turbine expansion work.

To ensure consistency across all evaluated conversion routes, the same LHV variation range was analyzed for the SRC, ORC, and EFGT systems. This range spans from the reference case of 1158 kJ/kg to approximately 2000 kJ/kg, corresponding to a variation of about 70% relative to the reference LHV.

Within this assessed range, the SRC efficiency decreases significantly as the fuel LHV is reduced. The thermodynamic sensitivity analysis indicates that, for larger capacities (1000–2000 kW), a reduction of approximately 70% in fuel LHV relative to the reference case leads to a relative decrease in net electrical efficiency of about 18%.

These results highlight the high sensitivity of SRC systems to fuel quality when operating with low-calorific gases, emphasizing the importance of maintaining sufficient heating value to sustain favorable steam generation and cycle efficiency.

For the ORCs, three different configurations were considered: without regeneration and with superheat (ORC A), with regeneration and without superheat (ORC B), and with regeneration and with superheat (ORC C). The working fluids considered were R245fa, MDM, and n-decane. The selection of working fluids was based on thermodynamic performance criteria, aiming to explore the operational range of ORC systems supplied with heat recovered from the combustion of charcoal production gases. Thermal stability limits, environmental aspects, and safety constraints, including flammability and handling requirements, were not addressed in detail and should be considered in subsequent engineering design stages. The values of efficiency and consumption of NCG for the different configurations of the analyzed ORCs were also retrieved from the Technical Report n°. 4 [26].

For the Organic Rankine Cycle (ORC), the thermodynamic performance was evaluated considering a fixed set of design parameters and the same range of lower heating values (LHV) of the carbonization gases adopted in the study. The simulations considered different power capacities between 100 and 2000 kWel and multiple working fluids, including n-decane and MDM, under configurations with and without regeneration and superheating.

The results indicate that the electrical efficiency of the ORC systems spans a relatively wide range, reflecting the strong influence of working fluid selection and cycle configuration. Based on the thermodynamic simulations, ORC efficiencies vary between approximately 5% and 24% across the evaluated power range. The highest efficiencies are achieved when using n-decane as the working fluid, particularly in configurations with

regeneration and superheating, while MDM also presents competitive performance and is currently employed in biomass-based ORC applications.

An additional sensitivity analysis was conducted to evaluate the influence of the fuel LHV on ORC performance. For the evaluated range of 1158 to 2000 kJ/kg, the results show that increasing the LHV leads to higher cycle efficiencies. In the case of n-decane, the efficiency increase associated with this LHV variation is approximately 10 percentage points, confirming the strong dependence of ORC performance on fuel energetic quality.

The Externally Fired Gas Turbine (EFGT) was evaluated at its nominal design point under ISO reference conditions [27] using the same average lower heating value (LHV) framework adopted in this study. The thermodynamic model represents steady-state operation of a small-scale externally fired gas turbine system fueled by charcoal carbonization gases, with performance indicators derived directly from mass and energy balances.

Under ISO conditions [27], the modeled EFGT presents a net electrical efficiency of approximately 16.7%. A parametric sensitivity analysis was conducted to assess the influence of the fuel LHV on system performance. The results indicate that the electrical efficiency of the EFGT exhibits a relatively low sensitivity to variations in fuel LHV when compared to Rankine-based cycles. For the evaluated LHV range of approximately 2000 to 7000 kJ/kg, the net electrical efficiency varies from about 15.8% to 16.8%, corresponding to a total efficiency variation of roughly 1 percentage point.

This limited sensitivity is a direct consequence of the externally fired configuration, in which the combustion gases do not expand through the turbine and primarily act as a heat source for the compressed air. As a result, reductions in fuel LHV lead to moderate efficiency penalties, allowing the EFGT to maintain electrical efficiencies on the order of 15–17% even when operating with low-calorific carbonization gases.

A comparative analysis of the influence of the lower heating value (LHV) of the carbonization gases on the evaluated conversion technologies reveals distinct thermodynamic behaviors. Among the assessed systems, the Steam Rankine Cycle (SRC) is the most strongly affected by variations in fuel LHV. This behavior is inherent to steam-based Rankine cycles, in which the thermal energy supplied by the fuel directly governs steam generation, turbine inlet conditions, and expansion work. Consequently, reductions in LHV lead to pronounced efficiency penalties, particularly at smaller plant scales.

The Organic Rankine Cycle (ORC), as modeled in this study, exhibits a significantly lower sensitivity to fuel LHV variations when compared to the SRC. This behavior is primarily associated with the presence of an intermediate thermal circuit and the use of high-boiling-point organic working fluids, which decouple the working fluid conditions from direct fluctuations in fuel energetic quality. Moreover, the ORC systems considered operate with high-temperature combustion gases rather than low-grade residual heat, allowing the cycle to maintain favorable thermodynamic conditions over a wide range of fuel LHV. As a result, variations in fuel LHV mainly affect the available thermal power and, consequently, the electrical output, while the conversion efficiency remains within a relatively bounded range.

The Externally Fired Gas Turbine (EFGT) presents the lowest sensitivity to variations in fuel LHV. Owing to its externally fired configuration, the combustion gases do not expand through the turbine but serve solely as a heat source for the compressed working air. This arrangement results in limited efficiency degradation under reduced fuel LHV, with variations on the order of one percentage point across a wide LHV range.

From a thermodynamic standpoint, these results indicate that SRC systems are best suited for applications with relatively stable and higher heating value fuels, ORC systems operating with high-temperature combustion gases provide improved robustness against fuel quality fluctuations, and EFGT configurations offer the highest tolerance to low-

calorific gases, albeit with lower absolute efficiencies compared to optimized Rankine-based systems.

To calculate the electricity generation potential in each municipality, it is necessary to consider that the efficiency of the SRC and ORCs changes depending on the cycle's operating parameters, which depend on the chosen generation capacity. Bearing in mind that charcoal production varies from municipality to municipality and, therefore, the efficiency of the steam cycle will change depending on the amount of gas available for electricity generation, it was necessary to build a correlation between the efficiency of the steam cycle and the gas consumption. The calculation of Net Electrical Power, in kW, was performed using Equation (2).

$$\text{Power} = \eta \times \text{LHV}_{\text{NCG}} \times \text{NCG flow [kW]} \quad (2)$$

where η is the efficiency of the electricity generation technology [%]; LHV_{NCG} is the lower heating value of non-condensable gases [kJ/kg]; and NCG flow is the mass flow rate of non-condensable gases [kg/s].

By multiplying these parameters, the net electrical power output of the system in kilowatts (kW) is obtained. This formulation enables the estimation of the conversion efficiency of non-condensable gases into usable electrical power, considering the performance of the selected electricity generation technology.

For the calculation of the NCG flow, it was considered that 21% of the production is carried out in high-performance kilns. This percentage comes from the cross-checking of annual production data and the number of ovens surveyed for each project; according to the yearly production per kiln and the data from Rodrigues and Braghini Junior [23], the type of oven most likely used in each CHPU is obtained. The number is also in agreement with that provided by Bailis et al. [29], who estimate that only 20% of national production takes place in high-performance kilns, with 80% in rudimentary ones. The NCG flow rate for high-performance furnaces was calculated according to Leme [30] for clustered furnaces of 200 tons of wood, through Equation (3):

$$\text{n}^{\circ} \text{ of kilns} = 3.0368 \times \text{NCG Thermal Power [MWt]} + 2.6689 \quad (3)$$

Based on the annual production data per CHPU, the estimated number of 200-ton kilns and the generated thermal power were calculated. From the power and the average LHV, the NCG flow for high-performance furnaces was calculated using Equation (4).

$$\text{NCG flow}_{\text{high efficiency}} = \frac{\text{NCG Thermal Power}}{\text{LHV}_{\text{average}}} \quad (4)$$

where $\text{NCG flow}_{\text{high efficiency}}$ is the mass flow rate of non-condensable gases in high-efficiency furnaces [kg/s]; NCG Thermal Power is the thermal power generated by the non-condensable gases [kWt]; and $\text{LHV}_{\text{average}}$ is the average lower heating value of the non-condensable gases [kJ/kg].

This equation allows for the estimation of the mass flow rate of NCG required to sustain the thermal energy demand of high-efficiency metal furnaces, providing a key parameter for energy recovery and optimization. On the other hand, the NCG flow for the 79% CHPU with low-efficiency kilns [29], the authors calculated that in "hot tail" furnaces, around 3167 kg of NCG are produced per ton of carbon-coal produced. According to the same study, each kiln has the capacity to produce 1.4 tons of carbon-coal per batch, totaling a production of 4.37 tons of NCG per kiln.

The estimated number of low-efficiency kilns was calculated considering the annual production of each CHPU and that each furnace produces batches of 2.3 tons of coal in

5 days of pyrolysis, totaling 62 batches per year. The NCG flow rate for low-efficiency kilns was calculated using Equation (5).

$$\text{NCG flow}_{\text{low efficiency}} = \frac{62 \times \text{n}^{\circ}\text{ of kilns} \times \frac{\text{kg NCG}}{\text{kiln}}}{\text{annual operation hours} \times 3600} \quad (5)$$

where $\text{NCG flow}_{\text{low efficiency}}$ is the mass flow rate of non-condensable gases in low-efficiency kilns, [kg/s]; 62 is the number of production batches per year for each kiln; n○ of kilns is the total number of low-efficiency kilns in operation; kg NCG/kiln is the amount of non-condensable gases produced per kiln per batch; annual operation hours is the total number of operating hours per year; and 3600 converts the time units from hours to seconds, ensuring that the NCG flow rate is expressed in kg/s.

This equation provides an estimate of the NCG flow rate required for low-efficiency kilns, contributing to the analysis of energy recovery potential in pyrolysis processes.

This work considered that the electricity generation plants would have 7447 h of annual operation (85% of the year).

Considering all the estimated power in each CHPU, the potential for thermal generation per municipality for 2020 is obtained. However, it is noteworthy that the calculated value is based on the CHPUs surveyed in the previous items. Therefore, it does not correspond to the State's total potential, as the production values found per CHPU were below expectations or projected for 2020.

2.4.3. Scenarios for Electric Power Generation

The considered scenarios were based on the variation in parameters inherent to charcoal production and electric energy conversion technologies: LHV of effluent gases, and the flow based on charcoal production over the projected years. Those related to conversion technologies are the technologies themselves with different thermal efficiencies.

To calculate the maximum potential for total electricity generation in the state, the maximum electrical efficiency that can be achieved through the generation technologies considered in the study was initially considered. An electrical efficiency of 30% was adopted, considering that through improvements in the projects of the ORC and SRCs, it is possible to achieve this efficiency value in the coming years.

To compare the results for each scenario, some indicators were also created. Based on the power, efficiencies, and gas consumption of each technology, the indicators of specific consumption of gas per MWh generated and electricity generated per ton of coal produced were calculated. The calculations of conversions and indicators were made following Equations (6) and (7):

Specific NCG flow per power indicator (SNCG):

$$\text{SNCG} = \frac{\text{NCG flow}}{\text{Power}}\ [\text{t/MWh}] \quad (6)$$

where NCGflow is the mass flow rate of non-condensable gases [ton/h], and Power is the net electrical power output of the system [MW].

A lower SNCG value indicates a more efficient process, as less NCG is needed to generate each megawatt of electricity.

Specific Energy Generation (SEG) Indicator:

$$\text{SEG} = \frac{\text{Energy}}{\text{Charcoal Production}}\ [\text{MWh/t}] \quad (7)$$

where Energy [MWh] is the total electricity generated [MWh] and Charcoal Production is the total mass of charcoal produced [tons].

A higher SEG value suggests a more energy-efficient process, as more electricity is generated per ton of charcoal produced.

The annual charcoal production needed to reach a specific power range in each conversion technology was also estimated. The calculation is based on the average NCG productivity in kg/h per ton of coal produced in the CHPUs. The amount of charcoal can be calculated using Equation (8).

$$\text{Charcoal} = \left(\frac{\text{NCG} \times 1000}{\text{Productivity}} \times \frac{1}{d_{\text{charcoal}}}\right)\frac{1}{1.2} \quad (8)$$

where

Charcoal is the annual charcoal production [mdc/year], where mdc refers to cubic meters of charcoal.

NCG is the mass flow rate of non-condensable gases generated during the carbonization process [kg/h].

Productivity is defined as the average NCG generation rate per unit of annual charcoal production, expressed as (kg NCG/h)/(ton charcoal/year). This definition implicitly accounts for the annual production basis.

d_{charcoal} is the bulk density of charcoal [kg/m^3].

The factor 1.2 is the volumetric conversion factor, indicating that 1 mdc of charcoal corresponds to 1.2 m^3 of charcoal.

2.5. Step 5: Economic Analysis

2.5.1. Steam Rankine Cycle—SRC

Capital Expenditures (CAPEX): To estimate the investment costs required for steam cycle technology, the investment calculation method recommended by Silveira [31] was adopted, based on the cost correlations proposed by Valero et al. [32], subsequently updated by Silveira et al. [31] and applied to thermoelectric plant studies by Pinto [33]. This methodology considers investments in the main components of the thermodynamic steam cycle (boiler, turbine, condenser, and pumps), fuel consumption, and a proportion factor relative to auxiliary equipment costs (20% of the expenses of the main component) for the calculation of the total investment cost [33]. Equations (9)–(13) below explicitly represent these investment cost correlations for each component and the calculation of the total investment (IT), following the methodology described above.

- Boiler:

$$I_{boiler} = 784 \cdot \dot{Q}_{boiler} \cdot \left[1 + \left(\frac{1 - 0.90}{1 - \eta_{boiler}}\right)^7\right] \cdot \left[1 + 5\, exp\left(\frac{T_S - 866}{10.42}\right)\right]\left[exp\left(\frac{P_S - 28}{150}\right)\right] \quad (9)$$

- Turbine:

$$I_{turbine} = 7490 \cdot E_P{}^{0.70}\left[1 + \left(\frac{1 - 0.95}{1 - \eta_{s,turbine}}\right)^3\right] \cdot \left[1 + 5\, exp\left(\frac{T_S - 866}{10.42}\right)\right] \quad (10)$$

- Condenser:

$$I_{condenser} = 1173\ \dot{m}_V \quad (11)$$

- Pump:

$$I_p = 3540 \cdot \dot{W}_p{}^{0.71}\left[1 + \left(\frac{1 - 0.80}{1 - \eta_{s,p}}\right)^3\right] \cdot 1.41 \quad (12)$$

- Total Investment:

$$I_T = 1.2 \cdot \left(I_{boiler} + I_{turbine} + I_{condenser} + I_p\right) \quad (13)$$

2.5.2. Organic Rankine Cycle—ORC

Capital Expenditures (CAPEX): To calculate the cost of acquisition of equipment (CAE), correlations by Turton et al. [34] for organic cycles were used. Mathematical expressions were developed based on the technical operating parameters for each component of the generation system. To calculate the costs with evaporator, turbine, and pumps, the Turton correlation presented in Equation (14) is used [11]:

$$log_{10}C_P^0 = k_1 + k_2\, log_{10}(A) + k_3[log_{10}(A)]^2 \quad (14)$$

where C_P^0 is the cost of acquisition of the related equipment; A is the technical parameter that characterizes the equipment capacity, such as, for the evaporator, it is the heat exchanged, and for pumps, the drive power, all in kW.

The values of the coefficients k_1, k_2, and k_3 for each of the components, as well as the correlation for the condenser and turbine-generator set, are presented in Table 7, where Q is the heat given off by the condensation system, and P is the electrical power produced in the generator. Therefore, the sum of all components presented in the cycle makes up the equipment acquisition cost.

Table 7. Coefficients and correlations for estimating the cost of equipment acquisition [34].

Component	Coefficients and Correlations
Boiler	$k_1 = 4.6656\ k_2 = -0.5157\ k_3 = 0.1547$
Pump	$k_1 = 3.3892\ k_2 = 0.0536\ k_3 = 0.1538$
Condenser	$C_P^0 = 12{,}300 \cdot \left(\frac{Q}{50}\right)^{0.76}$ Q unit is kW
Turbine and Generator	$C_P^0 = 1{,}850{,}000 \cdot \left(\frac{P}{11{,}800}\right)^{0.94}$ P unit is kW

The approach to defining the total installation costs of ORCs is based on the methodology presented in Lemmens [35], in which estimates are determined based on percentages of the cost of purchasing equipment for the cycle. The percentages applied to define the costs associated with the installation, operation, and maintenance of the generation system by the ORC were based on the average of the percentages applied by Bejan et al. [36] and are presented in Table 8.

Table 8. Parameters for calculating the total specific investment cost [35,36].

Fixed Investment (FI)	
Direct Fixed Cost (DFC)	
Local costs	
Equipment Acquisition Cost (EAC)	
Equipment installation	45% of EAC
Plumbing	31% of EAC
Instrumentation and control	10% of EAC
Electrical equipment and materials	11% of EAC
Off-site costs	
Structural work, civil construction, and architecture	44% of EAC
Work facilities	20% of EAC
Indirect Fixed Cost (IFC)	
Engineering and Supervision	30% of EAC
Construction Costs	15% of DFC
Contingencies	10% IFC
Legal costs	2% of IFC
Other costs: plant start-up costs	10% of the IFC

The ratio of the total costs associated with the installed capacity of the generation plant is referred to as the Specific Investment Cost (SIC), a parameter commonly used in preliminary economic analyses of ORC systems [37] and presented by Equation (15).

$$SIC = \frac{TIC}{\dot{W}} \quad (15)$$

The Total Investment Costs (TIC) are composed of the sum of the costs listed in Table 8, while $\dot{W}$ represents the plant's generating capacity. Furthermore, the cost correlations provided by Turton et al. [34] are based on US dollars for the year 2001, except for the cost of the generator set and the condenser, which refer to the year 2013 [38]. Therefore, costs must be updated to reflect the current economic situation. To achieve this, the CEPCI index (Chemical Engineering Plant Cost Index) is used. The most current value refers to the year 2019 (607.5), and the indexes for 2001 and 2013 are 397 and 567.3, respectively.

2.5.3. Externally Fired Gas Turbine—EFGT

In the case of externally fired gas microturbines, their current stage of technological development is considered emerging. The methodology is similar to that for ORCs, in which total costs are estimated as a percentage of the main equipment's acquisition cost, as outlined by Lemmens [35]. For the turbine manufactured by Ansaldo Energia, with a net power of 85 kW, Pantaleo et al. [39] report a specific cost of USD 4600.00 per kW. These costs include USD/kW 2370.00 for the turbine and USD/kW 3420.00 for the high-temperature heat exchanger. It is evident that the high-temperature exchanger significantly contributes to the overall cost of this equipment.

Applying the typical percentages for indirect and direct costs provided in Table 8 for the EFGT, the specific costs would amount to USD 8600.00 per kW.

2.5.4. Operation and Maintenance Costs (OPEX)

Fixed plant operation and maintenance costs include labor costs, insurance, maintenance, and replacement of equipment. These costs vary between 2% and 6% of the total installation cost per year [40]. Generating plants that run on renewable fuel tend to have lower operating and maintenance costs per kW, due to the scale of the plant. Variable costs of operation and maintenance, on average, are 0.0005 USD/kWh, and, therefore, are remarkably lower than fixed costs [41]. In places where low-cost biomass is available on a large scale and has affordable values, biomass can prove to be very competitive as an option for electricity generation.

The adopted parameters for the economic analysis carried out for the studied system are presented in Table 9. It was considered the fuel cost, as well as fixed and variable operating and maintenance costs, operating hours, and plant useful life.

Table 9. Selected economic parameters.

Parameter	Value	Reference
Operating hours	7447	-
Lifespan	20 years	-
Fuel gas cost (waste gas/no purchase costs)	USD 0.00	-
$C_{O\&M\ fixed}$	6% TI	[40]
$C_{O\&M\ variable}$	0.0005 USD/kW	[41]

2.5.5. Costs of the Gas Collection and Transport System and the Flare

The costs of the gas collection and transport system depend a lot on the layout adopted in the coal production yard. However, after consulting the leading charcoal producers who have already installed a gas collection system and transport pipelines, the cost of installing these pipelines is approximately USD 125.00 per linear meter of pipeline.

Burner costs depend on the number of kilns connected to it and the production capacity of each kiln, which may be different for each CHPU. Thus, as a reference, it was considered the costs of a burner capable of burning the gas flow of 18 kilns, with each kiln having the capacity to process 200 tons of wood at each carbonization cycle. Consequently, the burner costs are approximately USD 380,000.00. For other situations, with different numbers of furnaces connected to the burner, a direct relationship between the number of furnaces and the cost of the burner built for 1200-ton kiln was used, as the number of furnaces in operation defines the flow of gases and the volume of the burner.

2.5.6. Taxes and Fees

In addition to the gross amounts of CAPEX and OPEX, Brazilian law imposes certain taxes on a company's products and profits. The main taxes and rates considered in this work are described below.

The federal taxes considered in this study include IRPJ (Legal Entity Income Tax), CSLL (Social Contribution on Net Income), COFINS (Contribution for the Financing of Social Security), PIS (Social Integration Program)/PASEP (Public Servant Equity Formation Program), and IPI (Tax on Industrialized Products), in accordance with Brazilian federal tax regulations [42]. IRPJ, CSLL, COFINS, and PIS/PASEP are levied on corporate profits, whereas IPI and ICMS are levied on products. The ICMS rate applied in this study follows the regulation of the State of Minas Gerais [43]. The values adopted for taxes and fees are summarized in Table 10.

Table 10. Taxes and Fees Considered at Work.

	Taxes and Fees	Value
Levy on profit	IRPJ	25.0%
	CSLL	9.0%
	CONFINS	3.0%
	PIS/PASEP	0.65%
Levy on product	IPI	12%
	ICMS	18%

For clarity, the economic analysis follows a structured workflow in which component-level investment costs are first estimated and aggregated to obtain total CAPEX. Operational expenditures (OPEX) are then calculated based on fixed and variable operation and maintenance costs. Subsequently, an economic evaluation is performed in which applicable Brazilian federal and state taxes are applied to the corresponding economic flows, yielding the consolidated indicators used in the feasibility and sensitivity analyses.

2.6. Charcoal GHG Inventory in MG

This section estimates the contributions to greenhouse gas (GHG) emissions associated with charcoal production in Minas Gerais from a life cycle assessment (LCA) perspective. The system function considered is the complete combustion of charcoal, and the assessment consistently follows a cradle-to-grave approach, encompassing biomass production, carbonization, transport, and final use. Inventory data for the biomass production and carbonization stages were sourced from Alves e Silva et al. [17], which represents

a cradle-to-gate study, and were incorporated as upstream processes within the broader cradle-to-grave system defined in this work. The functional unit is defined as 1 ton of charcoal containing 70% fixed carbon on a dry basis. The system boundaries applied in this study are illustrated in Figure 2.

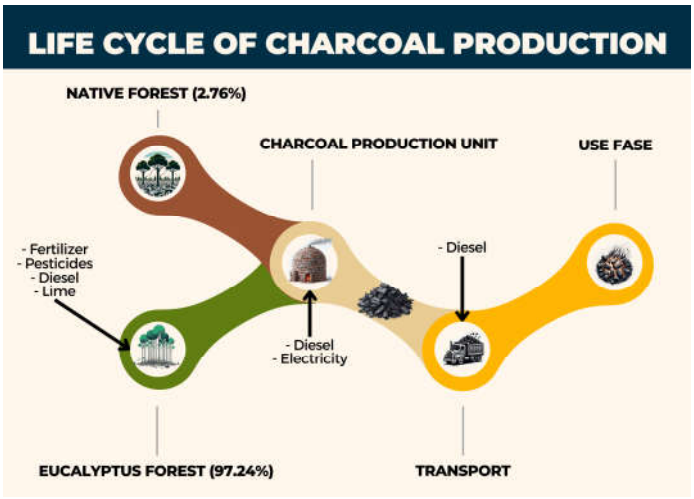


Figure 2. Life Cycle and GHG System boundaries for 1 ton of Charcoal Production in Minas Gerais.

The impact assessment method used for the characterization stage was IPCC 2013 GWP 100a, implemented in SimaPro® software, version 8.0.3.14 (ACV Brasil, Curitiba, Brazil), to quantify GHG emissions in terms of tons of CO_2 equivalents. Life cycle inventory data for background processes were sourced from the Ecoinvent® database (version 3). Primary foreground data were obtained from field measurements and literature sources representative of a Brazilian eucalyptus production system, as described by Alves e Silva et al. [17]. Data quality was ensured through the use of regionally appropriate datasets, consistency checks, and methodological coherence across the assessed system. No allocation was required within the main system, as no co-products were generated. For the consumption of secondary products, such as fuels, fertilizers, and pesticides, the cut-off allocation procedure was adopted. Emissions related to infrastructure and long-term carbon storage were not considered in this analysis.

A single scenario was assessed in this study. Eucalyptus feedstock was sourced from both planted and native forests. The biomass was carbonized using the technology described by Alves e Silva et al. [17]. After carbonization, the charcoal was transported to the site of use. In the use phase, it was assumed that all produced charcoal was completely combusted, resulting in the release of the corresponding amount of CO_2.

Charcoal produced from sustainably managed eucalyptus forests is generally assumed to have a neutral carbon balance, as the eucalyptus trees previously sequestered the carbon in the charcoal through photosynthesis. However, during charcoal production, methane (CH_4) is released during the pyrolysis stage, and diesel consumption occurs during the forest management, carbonization, and transportation stages. These emissions, particularly methane, need to be evaluated from a life cycle perspective following the ISO 14040 standards [44].

Eucalyptus forests sequester carbon from the atmosphere through multiple pathways. The most significant is photosynthesis, where trees absorb CO_2 and store it in their biomass—trunks, branches, leaves, and roots. According to Ribeiro et al. [45], eucalyptus plantations have demonstrated high levels of carbon sequestration, particularly in the soil, with the potential to store more than 674.17 tons of CO_2 per hectare. Furthermore, studies such as Zhang et al. [46] highlight that proper management practices, including minimal

soil disturbance and effective residue management, can enhance soil carbon retention in these plantations, contributing to long-term carbon storage.

Nevertheless, estimating carbon sequestration in eucalyptus forests presents challenges due to variations in management practices, soil types, and pre-existing natural conditions prior to forest implementation. Although the IPCC [47] provides guidelines for estimating soil carbon sequestration, this study does not include potential soil carbon sequestration due to the complexity of accurately estimating these variables in MG.

When assessing GHG emissions from charcoal production, it is essential to distinguish between sustainable production from eucalyptus reforestation and irregular production from native forest deforestation. Currently, 97.24% of charcoal produced in Brazil comes from eucalyptus plantations [48], with the remaining 2.76% derived from native forests. To account for deforestation-related emissions, a forest productivity of 100 m^3/ha and a wood density of 0.5 g/cm^3 were assumed. As reported by de Andrade et al. [49], approximately 19.9 tons of carbon are released per hectare due to logging activities. Additionally, emissions from native wood charcoal combustion and CO_2 released during pyrolysis are not considered carbon-neutral, contributing to the overall emissions.

To estimate life cycle emissions from CHPU and eucalyptus forests, this study uses data from Alves e Silva et al. [17], who conducted a cradle-to-gate LCA for eucalyptus and charcoal production in Minas Gerais. Gravimetric yields (GY) for charcoal from native forests are lower (22%) due to the use of inefficient technologies in irregular production, while eucalyptus-based production averages 26% [50].

Research demonstrates that improving carbonization technologies can significantly reduce emissions, primarily by increasing the GY [51]. Optimizing kiln temperatures and reaction conditions can increase the conversion of carbon into charcoal, reducing methane and other gas emissions. Based on the methodology from CDM [52], a GY of 26% results in 78.1 kg of CH_4 emissions per ton of charcoal produced. Lower yields (22%) result in higher emissions (99.7 kg of CH_4), while higher yields (33%) can reduce emissions to 40.6 kg of CH_4 per ton of charcoal [50]. These variations underscore the impact of carbonization efficiency on overall emissions. However, it is essential to note that CO_2 emissions associated with sustainable charcoal burning will be considered neutral in this context.

Emissions related to transportation will be calculated based on the average distance traveled by trucks to a distribution center, considering an average radius. The formula for the average distance within a circle will be used, Equation (16), assuming the distribution center is at the center of the circle and deliveries are uniformly distributed within this radius. The average distance (D_m) can be calculated using Equation (16), where R is the average radius [53].

$$D_m = \frac{3}{2} R \quad (16)$$

Transport emissions will be based on the following data from the Ecoinvent Database: 16–32 metric tons, EURO3 {RER} | transport, freight, lorry 16–32 metric tons, EURO3.

3. Results and Discussions

3.1. Results of the Survey on Charcoal Production Units

According to IBGE, the production of charcoal in MG was 5,207,154 tons, spread over 434 municipalities in 2020. The results are expressed in Figure 3 and Table 11.

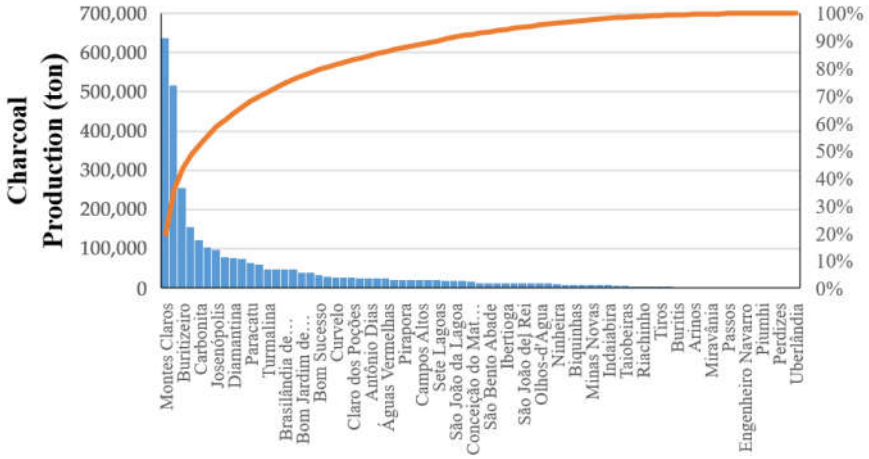


Figure 3. Pareto graph of the amount of coal produced by the municipality in 2020.

Table 11. Municipalities with the highest charcoal production in 2020.

Municipality	Prod. 2020 (Ton)	%	% Accum.
Montes Claros	637,915	20%	20%
João Pinheiro	516,395	16%	36%
Buritizeiro	256,732	8%	44%
Grão Mogol	155,465	5%	49%
Carbonita	124,200	4%	52%

The information collected by SISEMA resulted in more than 4000 licenses verified, with a total of 136 farms licensed to produce 14,010,674 mdc or 3,222,455 tons of charcoal. The research carried out in the PNLA resulted in only 32 licenses, with only 18 of them new in relation to SISEMA. Of the 18, only 5 had production data available, adding 7144 tons to the previous number. Overall, 154 projects were found with active environmental licenses in 78 municipalities, with a licensed production of 3,229,599 for the year 2020. The farms encompass at least 186 production units and 7080 kilns. The total number of kilns is probably much smaller than the real one, as a large part of the licenses did not present the information on the number of kilns, with 7080 being the number counted from the available information.

The North/Northeast region of the state stands out as the largest producer, being the area of high interest not only in relation to charcoal, but also in relation to the possible generation of electricity, which can be seen in "hottest" zones on the heat map presented in Figure 4. It is essential to highlight that the licensed production for 2020 is about 2,000,000 tons less than the 2019 real production.

It is noted that five municipalities are responsible for more than 50% of the state's production. They are: Montes Claros (20%), João Pinheiro (16%), Buritizeiro (8%), Grão Mogol (5%), and Carbonita (4%). In other words, despite the significant amount of charcoal, production is concentrated in a few municipalities in Minas Gerais. Unlike the production, 50% of the producers are spread across 11 municipalities. João Pinheiro stands out, being the 2nd largest producer, and the one with the largest number of farms. Meanwhile, Montes Claros is the largest producer with only 1 licensed farm.

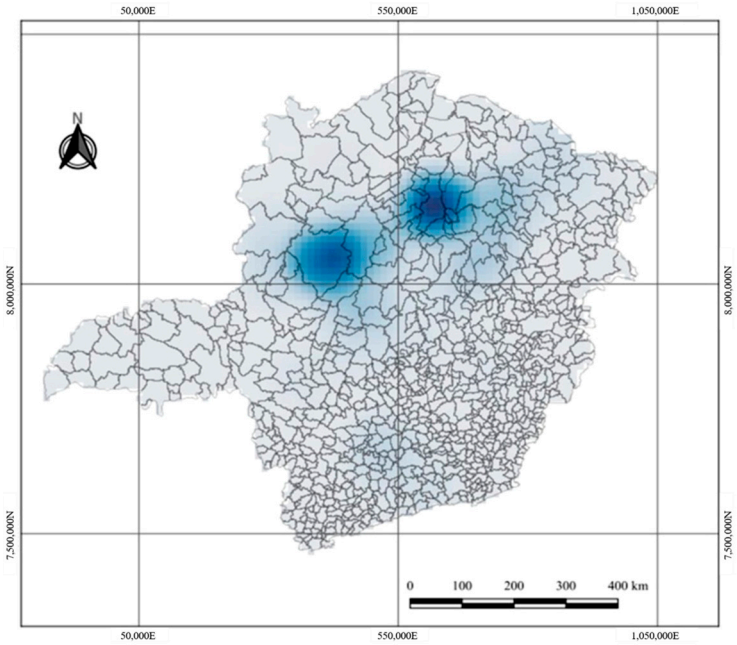


Figure 4. Heat Map of Charcoal Producing Regions in MG for the year 2020, highlighting (in blue) the regions that stand out as the largest producers.

Through the survey, it was found that some licenses do not have the annual production expressed in the document, or the license document is not available. This makes it challenging to estimate charcoal production, with the results being underestimated. Moreover, only a small portion of the licenses have charcoal production as their primary activity, meaning that all licenses raised by SISEMA were searched manually; in total, more than 4000 environmental licensing documents were verified. This leaves room for human error in the survey, and some licenses may have gone unnoticed during the survey. However, it is estimated to be a tiny error, as the most prominent producers are all listed with charcoal production as their primary activity.

Furthermore, many licenses do not describe the quantities or types of kilns and CHPUs, and it is not possible to obtain much information about the number of production units and kilns in operation. Added to these problems is the fact that there is a mismatch of data between the different systems (SISEMA and PNLA), where 18 projects were not listed in SISEMA and only 32 were available in PNLA. It is also observed that the licensed values for 2020 are far below the real value obtained in 2020 (about 38% below). All of this suggests that there is a big difference between the licensed value and the probable real production for 2020.

Regarding the difference in production between 2019 and that licensed in 2020, some reasons can be speculated. Amongst them:

- Licenses not found on data acquisition systems.
- Farms producing more than the license authorization.
- Farms producing without a license or with an expired license.
- Decrease in production due to the economic and health situation in 2020 because of COVID-19.

It is important to note that the plant-level technical and economic analyses presented in this study were conducted exclusively using licensed production data from state (SISEMA) and federal (PNLA) records. No correction or upscaling was applied to compensate for the difference relative to aggregated IBGE production statistics. As a result, the economic feasibility results should be interpreted as conservative (lower-bound) estimates of the tech-

nical and economic potential. This approach was adopted to avoid introducing speculative assumptions regarding the scale, technology, and operational characteristics of unlicensed or informally operating producers.

3.2. Charcoal Production Forecast in MG

To validate the forecast, a projection for the last 10 years of real data (2009 to 2019) was made, considering some previous data periods. The FORECAST.ETS function (from Microsoft Excel®) calculates or predicts a future value based on existing historical values. Thus, the function was tested with different values of the data history. The considered periods were the entire data period (1988–2008), the 10 years between 1999 and 2008, the 8 years between 2001 and 2008, the 5 years between 2004 and 2008, and the 3 years between 2006 and 2008. For each period, the mean relative error compared to the real data was calculated and presented in Table 12 and Figure 5.

Table 12. Validation for the last 10 years of real data.

Years	Time Period	Mean Relative Error
1988–2008	21	20.4%
1999–2008	10	12.2%
2001–2008	8	14.5%
2004–2008	5	17.1%
2005–2008	4	16.3%
2006–2008	3	15.9%

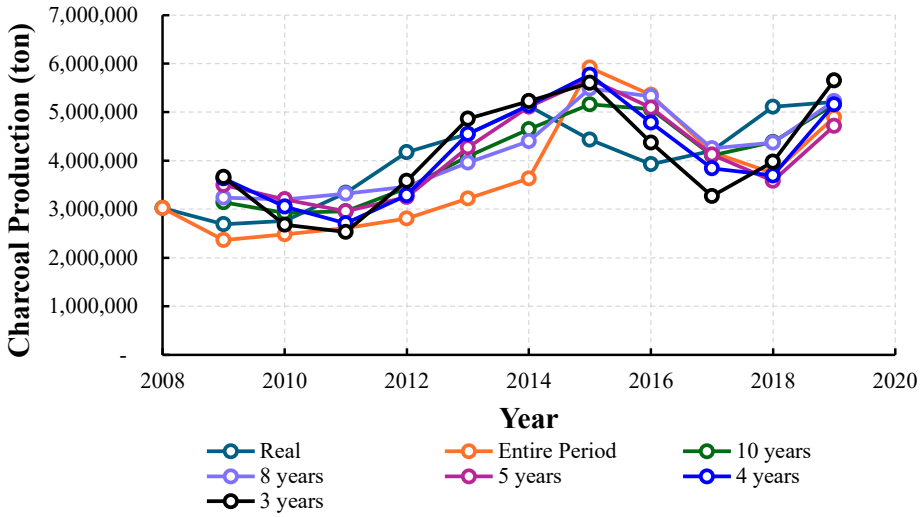


Figure 5. Comparison of data periods for forecast validation.

The forecast based on the last 10 years of data history presented the lowest mean relative error. In addition, the relative error for 2019 was only 0.8% in relation to the real data. By Figure 5, it is also visible that the forecast considering the period of the last 10 years of the history (blue line) is the one that comes the closest to the real data (red line). Therefore, future predictions (2000 to 2030) were based on the last 10 years of historical data (2010 to 2019).

The results for the total charcoal production forecast in Minas Gerais until 2030 are displayed in Table 13 and Figure 6. The average production growth rate obtained by the forecast is 2.64% per year, and there is an expected production of about 7 million tons of charcoal in Minas Gerais for the year 2030.

Table 13. Charcoal production forecast for MG based on the last 10 years of real data.

Year	Charcoal (Million Tons)
2019	5.2
	Forecast
2020	5.4
2021	5.6
2022	5.4
2023	5.7
2024	5.8
2025	6.1
2026	6.3
2027	6.5
2028	6,7
2029	6.8
2030	7.0
Yearly Growth Rate (%)	**2.64%**

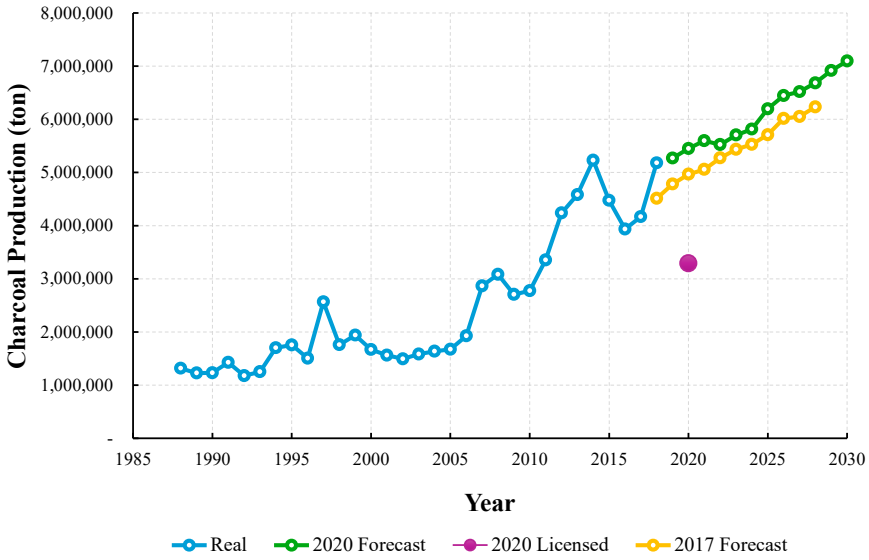


Figure 6. Projections of charcoal production in MG.

It can be noticed in Figure 6 that there was an exponential trend in the growth of production for the state over the years. Forecasts for 2017 and 2020, however, show less accentuated annual growth. It is also noticed that there is a significant discrepancy in the total amount licensed when compared to the historical series and forecasts.

3.3. Carbonization Technology

The carbonization technologies for each project were estimated according to information acquired from the survey in SISEMA and PLNA. The CHPUs that presented the number of kilns per production plant and the amount of charcoal produced per year were considered. The results show 29 units (78.4%) that possibly use primitive technologies (beehive, surface, and hot-tail ovens), and 8 units (21.6%) with advanced technologies (rectangular ovens made of masonry or metal, VMR). This corroborates the numbers estimated by Bailis et al. [29].

3.4. Estimate of Electric Generation Potential in Minas Gerais

Although installed capacity is reported in specific parts of this section to enable comparisons with existing thermoelectric infrastructure, the assessment of electric generation potential is primarily based on annual electricity generation. Accordingly, the results are presented in terms of GWh/year and MWh per ton of charcoal produced, which represents the effective energy contribution of the proposed systems.

The maximum electric power generation potential for each assessed technology and the specific energy generation per ton of charcoal produced are presented in Table 14. This table compares different energy conversion technologies in terms of their total estimated power potential (GW) and specific energy yield (MWh/ton of charcoal). The results highlight the differences in efficiency and energy recovery across the evaluated systems, providing important information about the most suitable options for power generation using carbonization gases in Minas Gerais.

Table 14. Total power and specific energy potentials by technology.

Technology	Maximum Power Potential [GW]	Specific Energy [MWh/ton of Charcoal]
30-efficiency technology	0.196	0.451
ORC C-n-decane	0.181	0.417
ORC B-MDM	0.156	0.359
EFGT	0.098	0.226
SRC	0.096	0.222
ORC A-R245fa	0.057	0.131

Due to the lack of statistically representative datasets at the state level, uncertainty propagation was not treated probabilistically. Instead, a scenario-based deterministic approach was adopted, in which contrasting kiln technologies, conversion pathways, and efficiency levels were evaluated to define a bounded technical envelope for electricity generation potential.

In this context, the interpretation of uncertainty relies on the explicit range of results obtained from the modeled scenarios rather than on statistical confidence intervals. The statewide extrapolation should therefore be understood based on the minimum and maximum electricity generation potential reported across the evaluated conversion technologies and production scenarios, as presented in Tables 14 and 15. Since all calculations are based exclusively on licensed production data, the reported values represent conservative, lower-bound estimates of the actual technical potential.

Table 15. Thermoelectric generation capacity installed in the State of Minas Gerais [54].

Fuel	Installed Capacity [GW]
Diesel and Fuel Oil	0.216
Coal	0.114
Natural Gas	0.382
Total Fossil Resources	**0.817**

3.4.1. Potential for Fossil Thermoelectric Generation Replacement Using Charcoal Carbonization Gases

The global energy transition requires reducing dependence on fossil fuels, especially in high-emission sectors such as conventional thermoelectric generation. In Brazil, thermoelectric plants (UTEs) still play a strategic role in the electricity grid, providing flexibility and

energy security. However, fossil fuels, such as diesel oil, coal, and natural gas, contribute significantly to greenhouse gas (GHG) emissions.

Although Minas Gerais has a lower installed thermoelectric capacity compared to other Brazilian states, it still operates fossil fuel-powered plants (Table 15). Replacing them is essential not only to reduce emissions, but also to the diversification of the state's electricity grid, aligning with national energy transition and decarbonization policies.

The SIGA database gives information on 363 thermoelectric generation plants in operation and fueled by fossil resources: diesel and fuel oil, natural gas, and coal, corresponding to an individual installed capacity of 0.22 GW, 0.38 GW, and 0.11 GW, 0.82 GW, respectively [54].

Given the total energy potential for each energy conversion technology addressed in Table 14 and the data from Minas Gerais's use of fossil resources for thermoelectric generation available in the Generation Information System [54], the charts presented in Figure 7 show the potential of replacing fossil fuels by combining charcoal production potential and the selected electric energy conversion technologies' output.

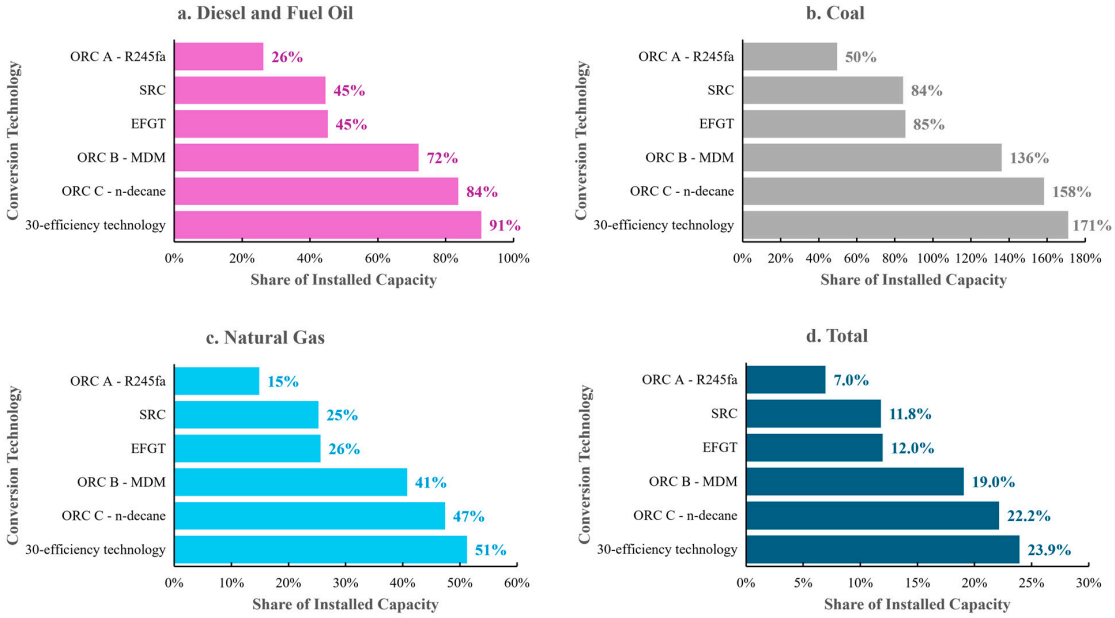


Figure 7. Fossil fuel replacing potential in thermoelectric generation (**a**) diesel and fuel oil; (**b**) coal; (**c**) natural gas; (**d**) total.

Therefore, it is notable that the most efficient energy conversion technologies can cover a significant share of the fossil resources individually, as in the case of diesel and oil fuel, Figure 7a, where the fossil fuel substitution ranges from 26 to 91 the case of coal, Figure 7b, it can be seen that we are dealing with the possibility of eliminating the use of this resource in the state altogether, at least when addressing the ORC B and C, or the 30%–efficiency technology. For Natural Gas, Figure 7c, the range of substitution is the lowest, 15–51%, but it can still be considered as a great opportunity as a complement to the energy supply, especially in periods when gas prices are peaking.

Finally, when addressing the total fossil resources portfolio, it is seen in Figure 7d that the equivalent electricity produced by the proposed systems can also avoid emissions indirectly in a range of 7–24%, as this is the amount of total fossil installed capacity it can replace in Minas Gerais. This transition could lead to a substantial reduction in CO_2 emissions and aligns with Brazil's long-term decarbonization policies, such as the PNE 2050 [55] and RenovaBio [56] programs.

Despite the potential benefits, replacing fossil-based power plants with carbonization gases faces technical, logistical, and economic challenges. The viability of this transition requires adequate infrastructure for transport and injection into the electricity grid, in addition to overcoming regulatory and financial barriers for its implementation and integration into the electricity sector.

3.4.2. Electric and Projected Generation Potential

With the estimated power in each CHPU, the potential for electricity generation per municipality for 2020 is obtained. However, it is noteworthy that the calculated value is based on environmental licensing. Such production values found per project were below the projected ones for 2020 by around 40%. However, unlisted charcoal producers are predominantly characterized by small or medium individual production units, with limited technological, financial, and institutional integration. While informal production may be relevant in aggregate terms, these producers typically operate with low-capacity and traditional systems, which constrain their participation in integrated energy conversion routes such as electricity generation [18,57]

From the potential values per municipality, it was possible to build distribution maps for the generation potentials of the different conversion technologies per municipality in 2020 (Figure 8).

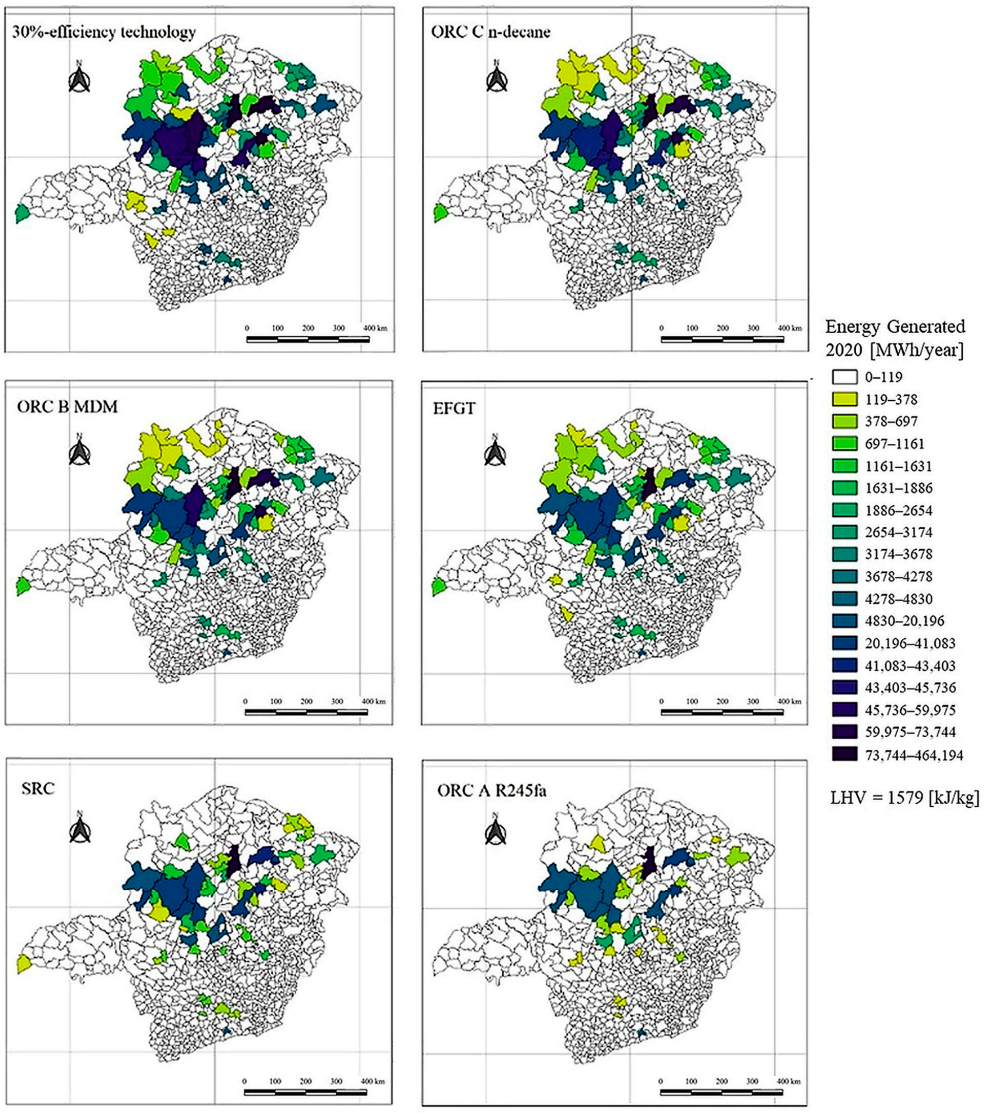


Figure 8. Power generation potential by technology.

With the maximum electricity generation potential (using technologies capable of achieving 30% efficiency), the generation potentials were divided into 11 categories, with the lowest being 0 (zero) and the maximum ranging from 73,744 to 464,194 MWh/year. In this way, it is possible to compare the existing generation potentials by municipality and observe the benefits of each technology in Figure 8.

The most significant potential achieved by the state in 2020 was 1348 GWh/year using the ORC C cycle, which has n-decane as the working fluid. The lowest potential was 423 GWh/year with ORC A having R245fa as the working fluid. The potential, considering a technology with 30% efficiency, would be 1457 GWh/year. The LHV considered in these results was the average value of 1579 kJ/kg.

The results of the previous items were extrapolated considering the production forecast for the state until 2030 and are shown in Table 16 and Figure 9.

Table 16. Results of the generation potentials forecast.

Year	Energy [GWh/Year]						
	ORC			SRC	EFGT	30% Efficiency Technology	Available
	A R245fa	B MDM	C n-decane				
2020	423	1159	1348	718	728	1457	4856
2021	438	1195	1389	743	748	1496	4988
2022	411	1132	1317	700	733	1467	4889
2023	444	1208	1404	752	760	1521	5069
2024	436	1191	1384	740	779	1557	5191
2025	454	1232	1432	769	822	1643	5478
2026	441	1201	1396	747	848	1695	5651
2027	438	1195	1390	744	871	1742	5807
2028	436	1189	1382	739	891	1781	5938
2029	436	1191	1384	740	912	1824	6081
2030	437	1191	1385	741	935	1869	6231

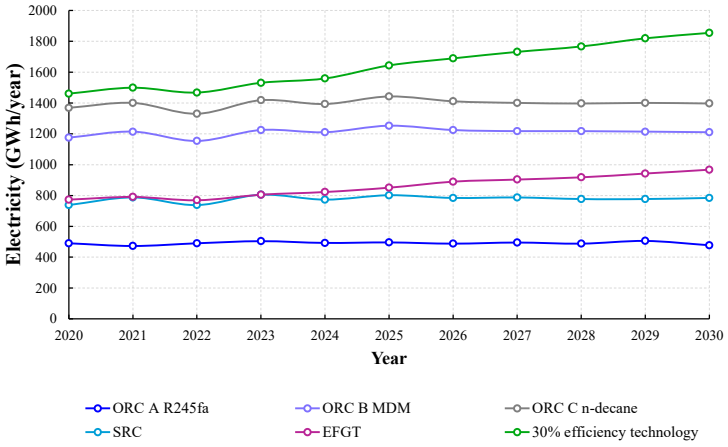


Figure 9. Results of the projection of generation potentials.

3.4.3. Generation Indicators

Indicators were calculated separately for high-performance and rudimentary kilns; these are presented in Table 17. As general results, the specific consumption of gas can vary from 7453 tons/year to 31,331 tons/year depending on the technology used and the type of kiln. The lower specific consumption of gas was generated from ORC with n-decane, which is likely due to the higher generation compared to other technologies. The ORC C scenario operating with n-decane has the lowest gas consumption per MWh, while ORC A with R245fa has the highest.

Table 17. Specific gas consumption per MWh generated.

Technology		Specific NCG Consumption [Ton NCG/MWh]		Specific Generated Energy [MWh/Ton Coal]	
		High-Efficiency Kiln	Rudimentary Kiln	High-Efficiency Kiln	Rudimentary Kiln
ORC A	MDM	11,756	20,990	0.36	0.11
	R245fa	20,711	71,911	0.20	0.03
	n-decane	8719	15,080	0.48	0.16
ORC B	MDM	8607	12,987	0.48	0.18
	R245fa	18,197	31,331	0.23	0.08
	n-decane	7571	11,109	0.55	0.22
ORC C	MDM	8449	12,667	0.49	0.19
	R245fa	16,857	28,653	0.25	0.08
	n-decane	7453	10,897	0.56	0.22
SRC		12,813	30,072	0.33	0.08
EFGT		15,199	15,199	0.27	0.16
ef = 30%		7600	7600	0.55	0.32

Regarding electricity generated, the scenarios ORC B and ORC B, operating with n-decane, are the most productive, being very close to each other, with values ranging from 0.22 (rudimentary furnaces) to 0.56 MWh/ton (high-performance furnaces), and 0.22 to 0.55 MWh/ton of charcoal, respectively. The lowest ratio of electricity generation per quantity of coal produced is observed in ORC A with R245fa, 0.03 MWh/ton of charcoal in rudimentary furnaces.

When comparing these results with a previous study [9], which estimated a generation of 0.76 to 0.93 MWh/ton of charcoal produced, this work presents lower values. This may be because the previous work made their predictions based on high-performance furnaces from only one plant, extrapolated to the entire production. Which, in fact, does not happen, as only a small portion is produced in such kilns, and the majority takes place in rudimentary, low-efficiency kilns.

The results demonstrated that the energetically better option is the ORC with regeneration and superheating, using n-decane as a working fluid, as it presents greater electricity generation with a lower consumption of NCG. Additionally, it requires less charcoal production, enabling its use in smaller plants. However, it is noteworthy that type A ORC with MDM and type B ORC with n-decane or MDM also presented similar results in terms of generation and consumption of NCG. In Figure 10, the annual energy generated by conversion technology is presented.

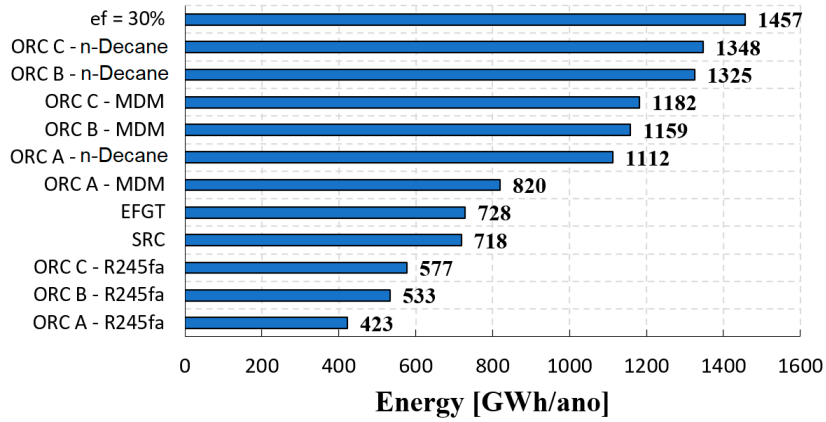


Figure 10. Total energy generated annually by conversion technology.

3.5. Economic Analysis Results

Based on the methodologies described in Sections 2.5.1–2.5.6, the economic results were obtained through the following procedure. First, component-level investment costs were calculated using the corresponding correlations for each technology and aggregated to determine the total capital expenditure (CAPEX) for a given plant capacity. Auxiliary infrastructure costs, including ducts, burner, and auxiliary heat exchanger systems, were then added. Operational expenditures (OPEX) were estimated from fixed and variable operation and maintenance costs, considering annual operating hours and plant lifetime. Subsequently, an economic evaluation was performed in which applicable Brazilian federal and state taxes were applied to the corresponding economic flows. Finally, the resulting values were calculated for different power levels and extrapolated for each charcoal production unit in the state, yielding the consolidated results presented in Table 18.

Table 18. Final OPEX and CAPEX for the different technologies adopted.

Technology	Costs + Taxes	Power [kW]			
		500	1000	1500	2000
SRC	CAPEX [USD millions]	2.87	4.50	5.90	7.14
	OPEX [millions USD/year]	0.72	0.12	0.17	0.21
ORC n-decane	CAPEX [USD millions]	3.92	6.59	9.05	11.52
	OPEX [millions USD/year]	0.99	0.17	0.24	0.31
ORC MDM	CAPEX [USD millions]	4.85	8.21	11.3	14.57
	OPEX [millions USD/year]	0.12	0.21	0.29	0.38
ORC R245fa	CAPEX [USD millions]	5.14	8.74	12.17	15.42
	OPEX [millions USD/year]	0.12	0.24	0.30	0.39
EFGT	CAPEX [USD millions]	4.35	8.24	11.86	14.61
	OPEX [millions USD/year]	0.15	0.20	0.29	0.37

3.5.1. Technical-Economic Feasibility

The technical–economic feasibility assessment is structured as a scenario-based analysis rather than a single-point evaluation. Electricity selling prices are varied in order to identify the minimum value required for economic viability under different boundary conditions. This approach allows the identification of feasible and non-feasible ranges across production scales and conversion technologies.

Within this framework, a 20-year lifespan and a minimum attractiveness rate of 10% were considered. By varying the energy sale price, an effort was made to identify a price at which at least the larger plants—accounting for 21% of the total production and operating high-efficiency ovens—could be viable and achieve a payback period within 10 years. The results are displayed in Table 19.

The lowest energy selling prices obtained are from the SRC. Even though it is not the technology that produces the greatest power and energy, it is still the one with the lowest cost. For productions below 100,000 mdc/year, the EFGT cycle incurs lower costs compared to the ORC using R245fa as the working fluid. Above this production, however, EFGT becomes more expensive, as its costs in such power range exceed those of ORC with R245fa.

Selling prices for each technology followed the same previous trend, with SRC first and ORC using R245fa last. In general, it is observed that while there is a decrease in the energy sale value for the SRC and the ORC with n-decane, the values increase for the other technologies. This fact is attributed to the significant rise in costs associated with increasing power, which is not adequately offset by the corresponding increase in energy sales.

Table 19. Energy Sale Prices for Economic Viability of Producers Using Advanced Kilns.

Plant	Municipality	Energy Sale Price [USD]				
		SRC	ORC n-decane	ORC MDM	EFGT	ORC R245fa
Vallourec Florestal Ltda.	Montes Claros	55.33	111.11	149.43	226.36	180.74
Arcelormittal Bioflorestas Ltda.	Carbonita	105.13	165.25	217.26	273.13	265.53
Viena Fazendas Reunidas Ltda./Fazenda Veredão	Grão Mogol	105.13	165.25	217.26	273.13	265.53
Gerdau Acos Longo Fazenda Biluca Gameleira Porto Alegre E Bom Retiro	Buritizeiro	113.23	172.80	226.62	278.90	277.36
Norflor Empreendimentos Agricolas S.A.	Josenópolis	115.48	174.86	229.17	280.44	280.58
Fazenda Sao Francisco	São Gonçalo Do Abaeté	124.90	183.23	239.51	286.62	293.70
Gerdau Aços Longos S/A—Fazenda Cabana Santa Bárbara	Três Marias	126.48	184.60	241.21	287.62	295.86
Gerdau Aços Longos S/A	João Pinheiro	127.30	185.31	242.08	288.13	296.97
Gerdau Aços Longos S.A./Fazenda Inhacica	Diamantina	128.14	186.04	242.98	288.65	298.10
Arcelormittal Sul Fluminense S.A./Fazenda Bom Sucesso E Riacho	Vazante	129.88	187.53	244.82	289.73	300.44
Fazenda Boa Sorte	Paracatu	136.70	193.29	251.91	293.82	309.48
Fazenda Aldeia Cachoeira E Amizade	João Pinheiro	155.42	208.33	270.40	304.18	333.12
Saint-Gobain Pam Bioenergia Ltda.—Bloco Fazenda Areão E Outros	Bom Jardim de Minas	169.05	218.68	283.07	311.04	349.41
Upc Fazenda Santa Rita	João Pinheiro	169.05	218.68	283.07	311.04	349.41
Fazenda Centenario	João Pinheiro	179.05	225.97	291.98	315.76	360.90
Novas Fronteiras Agro Negócios Ltda./Fazenda Gameleira, Marangaba E Estela	Buritizeiro	188.08	232.35	299.77	319.81	370.98
Fazenda Santo Antonio	João Pinheiro	188.08	232.35	299.77	319.81	370.98
Fazenda Jacurutu	João Pinheiro	188.08	232.35	299.77	319.81	370.98
Floral Agropecuaria Ltda.	Abaeté	207.49	245.46	315.75	327.92	391.74
Gerdau Aços Longos S/A—Fazenda Capão Do Retiro	Curvelo	207.49	245.46	315.75	327.92	391.74

The average energy sale price for processed gas practiced in auctions of the Electric Energy Trading Chamber (Câmara de Comercialização de Energia Elétrica—CCEE) from 2018 to 2020 was USD 71.23. The gradual increase in the auction price during the period is remarkable. However, due to the variation in the dollar exchange rate, the sale value decreases. Adopting the average sales price, it is evident that the current plants are all unfeasible, apart from the largest plant using SRC. The same is observed for the 2030 forecast.

It is noteworthy that sales prices can fluctuate significantly due to various factors. These include fluctuations in the dollar exchange rate, the international market for equipment purchases, the Brazilian hydrology scenario impacting electricity generation, changes in the energy matrix, the creation of incentive policies for certain modes of generation, and changes in taxes and tax exemptions. Despite this, as shown in Table 19, which displays the Energy Sale Prices for Economic Viability of Producers Using Advanced Kilns, these factors must be considered.

3.5.2. Economic Sensitivity Analysis

To evaluate the robustness of the feasibility results, a probabilistic sensitivity analysis was performed using a Monte Carlo approach. This analysis focuses on producers using the SRC technology, which represents the reference feasible case under the studied conditions, and aims to quantify the relative influence of key economic and operational parameters on the net present value (NPV).

Simulations were conducted by varying several factors, including the minimum attractiveness rate, taxes on products, taxes on profits, hours of operation, sales price of generated energy, and installed power according to the variation in LHV. Each variable was adjusted according to typical, triangular, or uniform distributions, as detailed in Table 20.

Table 20. Variables, Distribution type, and Variation used in the Sensitivity Analysis.

Variable	Distribution Type	Variation
Minimum Attractiveness Rate	Uniform	8–12%
Taxes on Product	Triangular	0–35%
Taxes on Profit	Triangular	30–40%
Hours of Operation	Normal	Stand.dev = 300 h
Energy Sales Price	Normal	Stand.dev = USD 4.47
Power	Normal	Stand.dev = 5280 kW (SRC) Stand.dev = 8103 kW (ORC n-decane)

Based on the variations and distributions mentioned above, 1000 simulations were performed using different random scenarios. Such simulations refer only to producers using SRC that presented energy sales value of up to 7 times the standard deviation of the historical values of 2018 and 2019, that is, sales prices up to USD 103.52. This is because, after some simulations with fictitious values, it was found that projects with sales prices above the stipulated have only 1% chance of a 10-year payback. In this way, only the plant located in Montes Claros presented a satisfactory value in relation to the energy price.

The plant using SRC has a 99.81% probability that the payback will occur within 10 years of operation. In this scenario, power is the variable that exerts the most significant influence on the NPV of the 10th year, followed by the energy sale price, minimum attractiveness rate, operating hours, taxes on products, and taxes on profits.

As expected, power, sales price, and hours of operation have a positive relationship with NPV; if they increase, the profit also increases. On the other hand, the minimum attractiveness rate and taxes have a negative relationship with the NPV (Figure 11).

For comparison purposes, the same simulations were carried out for a fictitious project with 10 MW of installed power. There was a drastic reduction in the payback in 10 years, with a chance of only 18.64% under these operating conditions.

Furthermore, it is explicit in Figure 12 that the component that has the most significant influence for a 10 MW plant is the energy sale price, with the installed capacity appearing in penultimate place. Taxes on products appear in 2nd place, followed by the minimum attractiveness rate, power, and taxes on profits.

The difference in the sensitivity analysis between the Montes Claros project, with more than 60 MW, and the fictitious 10 MW project may be due to some factors. As CAPEX and OPEX are related through an exponential adjustment, they are more significant at higher powers. At 10 MW, the costs still have a considerable weight in the initial investment. Such weight is even greater for smaller powers, being perhaps the biggest obstacle to the viability of the projects. In other words, as much as greater powers generate more energy, their costs still exceed the profit obtained from the energy sale.

As product taxes directly influence CAPEX, it is to be expected that they will also significantly contribute to the variation in initial CAPEX investment, especially for smaller powers. Similarly, taxes on profits also exert a negative influence, reducing part of the income, but in a milder way, as demonstrated by the simulations.

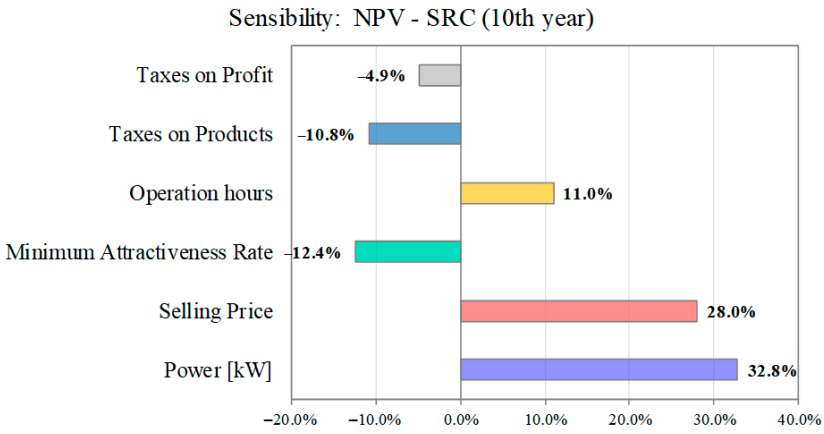


Figure 11. Contribution of each variable in the simulations for the Montes Claros project using SRC.

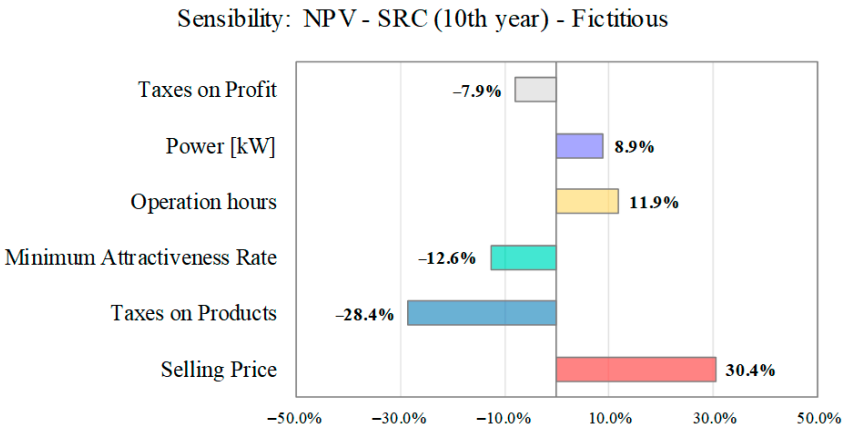


Figure 12. Contribution of each variable in the simulations to a fictitious 10,000 kW enterprise using SRC.

In the case of the 60 MW plant, profits end up being higher due to the large volume of energy generated. Thus, a positive variation in the LHV would exert a significant influence on the NPV, supplanting the initial CAPEX investments and reducing the impact of taxes on the initial equipment acquisition.

Therefore, the sale price also becomes a fundamental variable in the viability of charcoal producers that wish to operate electricity generation plants from the effluent gases from wood pyrolysis. In both simulations, the energy sale price has a contribution of about 30% in the variation in the NPV. TMA has a similar influence in both projects, ranging from 10% for 10 MW to 12% for 60 MW.

To better study the influence of the equipment acquisition cost on the feasibility of the projects, the same simulations were carried out in the fictitious project, but with CAPEX values 10% and 25% lower than those calculated previously for the SRC.

With a 10% discount on CAPEX, it was possible to verify an increase in the probability of payback in 10 years from 18.64% to 47.12% (Figure 13) and a reduction in the sale price of energy by around 8.5% for all projects.

For a 25% reduction in CAPEX, there was an increase in the probability of payback in 10 years to 87.36% (Figure 14) and a 19.9% reduction in the energy sale price for all projects. Such results show once again the importance of the equipment acquisition cost in the viability of such projects and demonstrate the need to further develop the electricity conversion technologies for effluent gases in terms of conversion efficiency, besides equipment and operating costs.

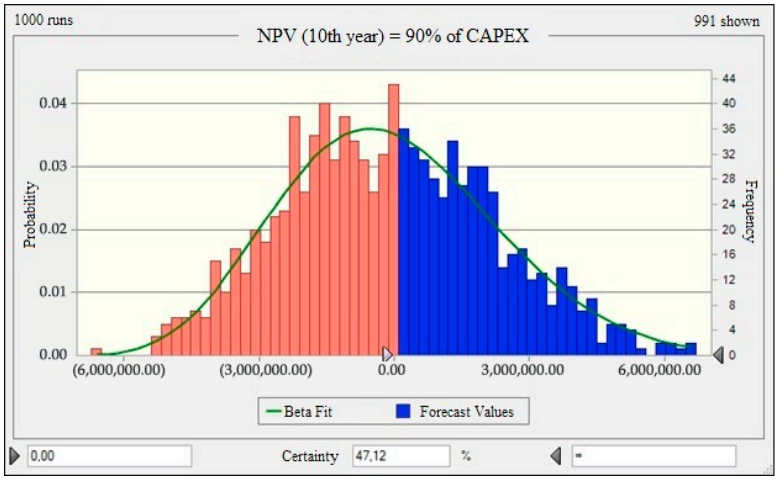


Figure 13. Frequency of values for NPV in the 10th year for a fictitious 10,000 kW project using SRC with a 10% discount on CAPEX.

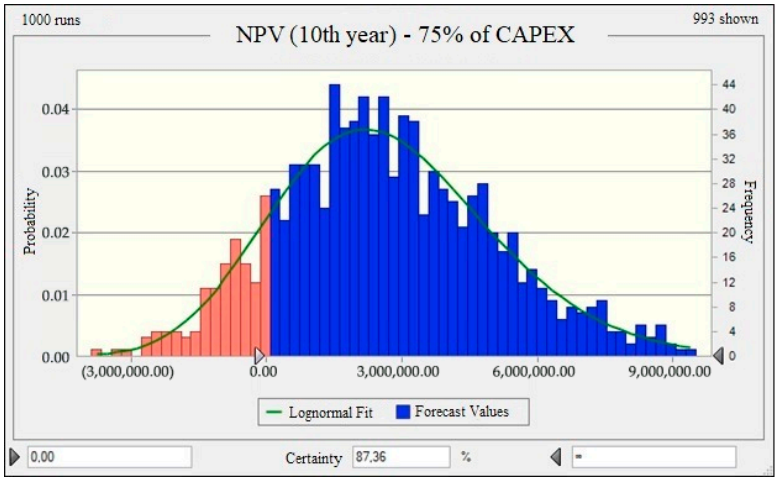


Figure 14. Frequency of values for NPV in the 10th year for a fictitious 10,000 kW project using SRC with a 25% discount on CAPEX.

3.6. Charcoal GHG Emissions Inventory in MG

This section presents the greenhouse gas (GHG) emission results of the life cycle assessment. Results are reported per functional unit of 1 ton of charcoal containing 70% fixed carbon on a dry basis and refer to a cradle-to-grave system boundary, encompassing biomass production, carbonization, transport, and final use through complete combustion.

The life cycle of charcoal production in Brazil involves multiple stages, each with distinct environmental impacts. It begins with raw material sourcing, primarily from eucalyptus plantations (97.24%) and native forests (2.76%). After a growth period, the trees are harvested, and the wood undergoes carbonization in masonry kilns. Post-carbonization, the charcoal is sorted, graded, and packaged for distribution. It is then transported to markets for various uses, including domestic heating, industrial applications, or steel production. The efficiency and emissions of charcoal vary depending on the end-use technology, and after consumption, the residual ash can either be disposed of or repurposed as a soil amendment.

In the forestry production subsystem, eucalyptus seedlings are sourced externally, and diesel is used for soil preparation, planting, harvesting, and transportation operations. Limestone is applied during soil preparation to regulate pH levels, while agrochemicals like glyphosate for weed control and sulphuramid for pest control are used throughout the

growth cycle. Fertilization, particularly with nitrogen (N), phosphorus (P), and potassium (K) in NPK formulations, occurs during both the initial soil preparation and the maintenance phases. GHG emissions stem primarily from intensive mechanization (CO_2, CH_4, and N_2O emissions from fossil fuel combustion in machinery), biomass burning, the application of limestone (CO_2 emissions), and nitrogen fertilizers (N_2O emissions) [17,58].

The CHPU subsystem includes the reception of eucalyptus wood, the carbonization process, and the dispatch of the resulting charcoal. Diesel is used for wood handling and dispatch operations, while electricity is consumed for office activities and lighting within the CHPU facility [16]. Table 21 presents the greenhouse gas (GHG) emission contribution breakdown for this subsystem within the cradle-to-grave system.

Table 21. GHG Inventory Results to produce 1 ton of Charcoal in Minas Gerais.

Total	Native Forest	Eucalyptus Forest	CHPU Native	CHPU Eucalyptus	Transport	Use Fase	
2495.7	0.18	62.26	126.57	2184.50	51.34	70.84	kg CO_2 eq
100.0%	0.01%	2.49%	5.07%	87.53%	2.06%	2.84%	%

The estimated carbon footprint of charcoal production in Minas Gerais is 2495.7 kg CO_2eq per ton of charcoal. Scaled to the state level, this represents an estimated total of 12.6 million tons of CO_2 emissions annually from charcoal consumption.

The results indicate that the CHPU subsystem is the largest source of GHG emissions, contributing approximately 92.43% of the total emissions (Native and Eucalyptus CHPU). This is mainly due to CO_2 and CH_4 emissions during the pyrolysis process, which account for 90.36% and 1.26% of the emissions, respectively. Notably, CO_2 emissions from eucalyptus wood pyrolysis are considered biogenic, whereas CO_2 emissions from native wood are not, highlighting the unsustainable nature of deforestation and its net carbon release.

The second largest contributor to GHG emissions is the use phase, driven by the combustion of native wood charcoal. Native wood does not contribute biogenic CO_2, and when emissions from deforestation, pyrolysis, and combustion are combined, native forest wood utilization accounts for 8.11% of total GHG emissions. This highlights the critical environmental cost associated with the continued use of native wood for charcoal production, even though it represents only a small percentage of overall charcoal consumption.

Interestingly, the eucalyptus forest subsystem, which supports 91.24% of charcoal production, contributes only 2.49% of total emissions. These emissions are primarily due to forest management activities like planting, fertilization, and machinery use. In contrast, the transportation phase accounts for 2.06% of total emissions, reflecting its relative modesty compared to the carbonization and native wood use phases. Studies like Araújo et al. [59] emphasize the need for more efficient logistics and the potential of lower-emission transportation, such as biofuel use.

When compared to similar studies, these findings align with earlier assessments that identify carbonization as the most emission-intensive phase of charcoal production. Studies by Gonçalves et al. [58], Vicente Leme et al. [16], and Silva et al. [18] similarly highlight the critical role of CH_4 emissions from carbonization in shaping the overall GHG footprint of charcoal.

Further mitigation efforts in charcoal production should focus on: (1) implementing CH4 afterburners; (2) eradicating the use of native forest biomass; and (3) increasing the GY of the process to reduce biomass consumption and diminish CH_4 emissions during pyrolysis. To assess the impact of these measures, four charcoal production scenarios will be evaluated: (A) native wood charcoal production with a GY of 22%; (B) eucalyptus wood charcoal production with a GY of 26%; (C) eucalyptus wood charcoal production with a GY

of 33%; and (D) eucalyptus wood charcoal production with a GY of 33% and incorporating afterburners whit 80% efficiency. The comparative results are presented in Figure 15.

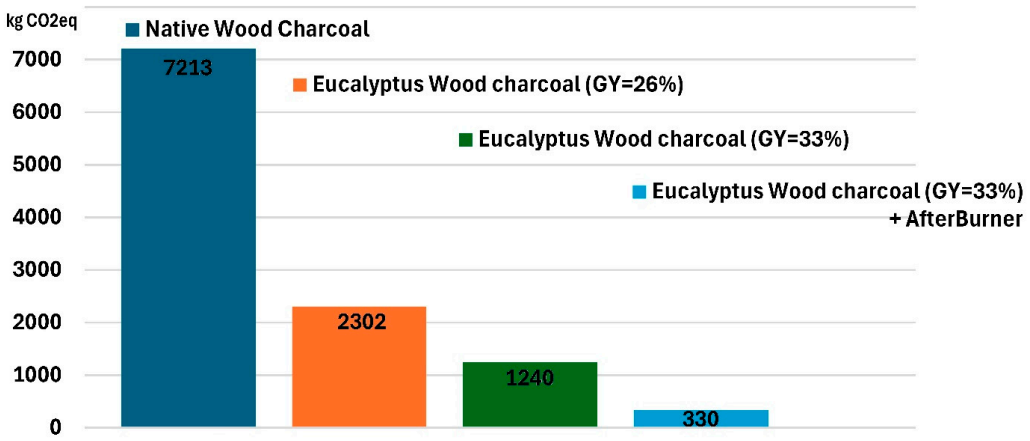


Figure 15. Comparative LCA of GHG emissions for charcoal production options (kg CO_2eq/ton of charcoal).

The results indicate that implementing measures 1 to 3 can significantly reduce the charcoal carbon footprint. Option (D), which incorporates sustainable forests, a high GY, and afterburners, results in only 4.6% of the GHG emissions compared with option (A), which relies on native forests and low technology practices.

For instance, if the use of native forests for charcoal production were eliminated in MG, the average state GY jumped from 26% to 33%, and, at least, the larger plants (21% of total production) adopted gas burners, the carbon footprint could decrease to 1049.1 kg CO_2eq per ton, representing a 57.0% reduction from current levels.

These results highlight the significant environmental benefits of using eucalyptus plantations for charcoal production, as they sequester carbon and provide a renewable biomass source. By reducing reliance on native forests and improving carbonization technology to curb CH_4 emissions, the environmental impact of charcoal production in Minas Gerais can be significantly reduced. Policymakers and industry stakeholders should promote modern, efficient kiln designs and ensure that charcoal production is sourced exclusively from sustainably managed plantations.

4. Conclusions

This work proposes a survey of the potential for electricity generation from effluent gases from charcoal production plants in Minas Gerais through an analysis of current charcoal production and available electricity conversion technologies. During the survey of charcoal producing units, a disparity was noted between the value consolidated by IBGE and the amount licensed, through state (SISEMA) and federal (PNLA) databases. Such disparity may be due to licenses not found in the data acquisition systems, charcoal farms producing more than the licensed, producers without a license or with an expired license, and the decrease in production due to the economic and health situation of 2020 due to COVID-19.

The results show a concentration of charcoal production in the North and Northeast regions of Minas Gerais, with only 5 municipalities accounting for more than 50% of the state's production. On the other hand, the production forecast for 2030, showed an annual growth rate of 2.64%, with an estimated production of 7.0 million tons for the year 2030.

Considering the plants surveyed, it is estimated that 21.6% use advanced charcoal production technology, with the remaining 78.4% still using primitive production technolo-

gies. The area of eucalyptus planted to supply the 2020 production was estimated to be 40,440 hectares.

The greatest generating potential reached for the State in 2020 was 1348 GWh/year using the ORC with regeneration and superheating, having n-decane as the working fluid. EFGT and SRC present intermediate values of 728 GWh/year and 718 GWh/year, respectively. The lowest potential was 423 GWh/year with ORC A having R245fa as the working fluid. The potential considering a technology with 30%-efficiency was 1457 GWh/year. Based on the charcoal production forecast, it is estimated an electric potential of 6231 GWh/year for 2030.

The analysis indicates that, from an energy perspective, the best option is the ORC with regeneration and superheating using n-decane as working fluid. However, economically, plants utilizing rudimentary charcoal production technology are all unfeasible. Among those with advanced technology, only the Montes Claros project using SRC or ORC with n-decane achieved an energy sales price within the historical range of 2018–2020 (below USD 71.23).

The economic sensitivity analysis revealed that projects selling energy below USD 103.52 are unlikely to achieve a 10-year payback under current conditions, making most charcoal production in the state economically unviable, except for producers capable of installing an SRC plant with at least 10 MW capacity. Furthermore, the energy sales price emerged as the most influential factor in project viability, particularly for plants below 10 MW. Other key factors include taxes, minimum attractiveness rate, operational hours, effluent gas composition (LHV), and profit-related taxes. Additionally, a 10% reduction in CAPEX led to an 8.5% reduction in the energy sale price, while a 25% CAPEX cut resulted in nearly a 20% price reduction. The current technical and economic conditions are not favorable for implementing electricity generation plants based on energy reuse from effluent gases in charcoal production. Key obstacles include the low efficiency of kilns used in carbonization and the high costs and low conversion efficiencies of existing technologies.

However, it is worth emphasizing the energy and environmental benefits from this reuse. Significant efforts would be necessary to increase the efficiency and uniformity of the producers' kilns and the maturity of conversion technologies. These efforts would likely require by economic and environmental incentives, such as tax exemptions and incentives tied to reducing greenhouse gas emissions and improving energy efficiency.

The energy transition path includes adopting low-carbon technologies in hard-to-abate processes like steel making. Given the 2.64% estimated annual growth in Charcoal production and total production of 7.0 million tons by 2030, along with the charcoal production's significant contribution to the state's GHG emissions, it is mandatory to change.

In this sense, the proposed methodology of implementing afterburners to increase the gravimetric yield from 26% to 33% can directly reduce steel-making emissions by means of increased energy efficiency, besides eliminating the use of biomass from native forests. Besides indirectly avoiding emissions by replacing the use of fossil fuels in thermoelectric generation.

Brazil is known for its vast availability of biomass, which translates into a large bioenergy source, an occurrence that also applies to Minas Gerais. However, eliminating the use of forestry biomass, which is low energy conversion residues, and substituting it with more efficient energy conversion technologies without applying fossil resources would decrease emissions by 57%, lowering the carbon footprint associated with charcoal to 1049.1 kg CO_2eq per ton.

Charcoal carbonization gases have a high potential to replace fossil-based thermoelectric plants, eliminating the use of coal, reducing diesel consumption by up to 91%, and replacing up to 51% of natural gas. In total, the replacement can reach 23.9% of fossil

capacity in Minas Gerais, promoting the energy transition and aligning with the National Energy Plan for 2050 (PNE 2050) goals and the decarbonization of the electricity sector.

Therefore, contributing to the energy transition and sustainability in Minas Gerais passes through the iron and steel industry losing its dependence on forestry biomass resources, which would also contribute to avoiding the use of fossil fuels. Thus, this contributes to the transition towards modern carbonization technologies, which have been proven to mitigate their environmental impact.

The quantified electricity generation potential from charcoal carbonization gases indicates that, at a state scale, this resource could represent a relevant contribution to the electricity mix in Minas Gerais. While this study does not model power system dispatch or fuel substitution, the magnitude of the estimated potential suggests that energy recovery from carbonization gases may support future strategies aimed at reducing the reliance on fossil-based electricity generation.

Future research should focus on reducing key uncertainties and advancing the technological readiness of electricity generation from charcoal production gases. This includes dedicated field measurements in representative charcoal production units to better characterize non-condensable gas (NCG) flow rates, composition, and LHV variability under real operating conditions. In parallel, pilot and demonstration projects should be developed to evaluate the operational performance, availability, and integration challenges of SRC, ORC, and EFGT systems coupled to gas collection and afterburning units. Additional efforts should focus on optimizing and reducing the cost of gas collection and transport infrastructure, including modular layouts and aggregation strategies for small and medium producers. Finally, future studies should expand the economic and environmental assessment by incorporating policy instruments, tax incentives, and avoided-emission credits, in order to evaluate realistic deployment pathways and scaling potential at the regional and national levels.

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Abbreviations

The following abbreviations are used in this manuscript:

BF-BOF	Blast furnace/oxygen converter
CAPEX	Capital expenditure
CEPCI	Chemical Engineering Plant Cost Index
CHPUs	Charcoal Production Units
CNAE	National Classification of Economic Activities
COFINS	Contribution for Social Security Financing
COPAM—MG	Minas Gerais State Environmental Policy Council
CSLL	Social Contribution on Net Income
EFGT	Externally Fired Gas Turbine
GHG	Greenhouse gas
GY	Gravimetric yields
IBAMA	Brazilian Institute of Environment and Renewable Natural Resources
IBGE	Brazilian Institute of Geography and Statistics
IPI	Tax on Industrialized Products
IRPJ	Legal Person Income Tax
LCA	Life Cycle Assessment
LHV	Lower Heating Value
NCG	Non-condensable gases
OPEX	Operation and maintenance expenditure
ORC	Organic Rankine Cycle
PASEP	Program for the Formation of Equity of the Public Servant
PIS	Social Integration Program
PNLA	National Environmental Licensing Portal
SEMAD	State Secretariat for the Environment and Sustainable Development
SISEMA	State System for the Environment and Water Resources of Minas Gerais
SRC	Steam Rankine Cycle
TRL	Technological maturity level

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