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Energy Performance of Different Charcoal Production Systems

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Abstract: This study aimed to assess the energy performance of three different charcoal production systems: "encosta" kiln, "rectangular" kiln, and "fornalha" kiln. Data collection involved measuring carbonization product yields and essential process variables, enabling determination of material and energy flows, and evaluation of two main energy indicators: the EROI and the energy balance. The study found that all evaluated systems had a negative energy balance, indicating inefficiency. The encosta kiln system displayed the best energy performance with the highest EROI (0.90 ± 0.45) and the greatest energy intensity (264.50 MJ t^{-1} ± 132.25), despite having faced technological, operational, and mechanization limitations that explained its limited use on a global scale. Research that evaluates the sustainable production of charcoal has grown in recent years, however, and it is necessary to invest in studies that evaluate the existing energy flow. Thus, the energy performance indicators presented in this study offer valuable insights for decision-making in charcoal production, potentially maximizing efficiency of the systems. Optimizing carbonization system energy performance can be achieved by implementing operational parameters focused on reducing avoidable energy losses, such as improving thermal insulation and introducing systems for heat recovery or combustion gas utilization.

Keywords: energy balance; material flow; environmental analysis; charcoal kilns; EROI

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1. Introduction

Charcoal is considered an essential secular energy source, mainly in developing countries such as Brazil, Sub-Saharan Africa, Southeast Asia, and Haiti [1]. It is estimated that 50% of the wood extracted from forests worldwide is used as fuel; of this, about 17% is converted into charcoal [1]. Its main applications involve the domestic and industrial sectors, through heating, cooking, baking, and brick and cement manufacturing. In Brazil, almost 90% of its 6 million tons per year are destined for the steel industry, to be used as a reducing agent in the production of pig iron and steel [1–3]. Approximately one-third of the world's population depends on this fuel as an energy source, and more than 40 million people around the globe use charcoal production as a source of income.

In this critical scenario, global charcoal production has tripled in the last 54 years, from 17.3 million tons in 1964 to 53.2 million tons in 2018 [1], and the expectation is that it will continue to increase in the coming decades [1]. However, the significant technological changes in the different production systems that involve the production of charcoal do not equal this considerable increase in volume [4–6]. The "carbonization" process used by ancient civilizations, such as the Egyptians, Persians, and Chinese, remains almost unchanged today, especially when considering the point of energy loss, which can reach more than 50% of the energy content of the biomass [7]. Thus, despite the technological innovations encompassed by the forest landscape in recent years, the world energy sector is still based on the use of rudimentary ovens, often characterized by limited control and efficiency of the process [4–6]. This is a reality in many countries, such as Nigeria, Kenya, and Thailand, whose primary interest has been domestic use, and even Brazil, which meets a great steel demand [8].

The search for efficient production systems that associate the understanding of variables related to processes and energy balance can positively contribute to the rational use of resources and raw materials, cost reduction, and increase in the efficiency of inputs, in addition to promoting energy savings and the consequent appreciation of the product in the consumer market [8–10]. This is mainly because the efficiency of converting wood into charcoal is an essential qualitative tool that guides the productivity of the process and, at the same time, informs its performance, mass balance, and quality of the final product, among other variables relevant to the process of charcoal production.

Based on this, it is imperative to conduct a thorough analysis of the existing factors, identifying those with the highest impact on the technological process, while eliminating insignificant or minimally impactful factors [11]. These considerations encompass aspects related to mass and energy losses during wood carbonization, as well as the efficiency of the production systems, characterized by the various kilns used to preserve the essential energy conversion from wood to charcoal. Despite the existence of multiple production systems for charcoal derived from wood, the comprehensive understanding of carbonization thermodynamics on a production scale, integrating mass and energy balances, remains in its infancy, despite the global importance of charcoal as an energy source. This study, therefore, represents an innovative endeavor aimed at bridging this knowledge gap by providing invaluable insights capable of enhancing charcoal production. While recent research has explored the productive efficiency of charcoal kilns, our approach goes beyond this by scrutinizing the intricate energy flow dynamics, offering a unique perspective on this critical aspect of the charcoal production process [12–14].

This distinctive focus on the interplay of energy in various charcoal production systems offers a novel dimension to the field, setting the stage for potential advancements and optimizations that could drive significant improvements in the industry's sustainability and performance. In light of these objectives, several pivotal questions necessitate investigation: (i) What comprises the energy balance concerning the inputs and outputs of charcoal production systems? (ii) Does a charcoal kiln that yields higher outputs consume more or less energy to produce a given volume of charcoal? (iii) Can this energy expenditure be offset by the gravimetric yield achieved? As such, this study embarks on an inaugural exploration into the energy performance of diverse systems employed in global charcoal production.

2. Materials and Methods

2.1. Description and Selection of Charcoal System Variables

This research investigated three charcoal production systems that are very common in some countries, such as Uganda, Cambodia, and Brazil: "encosta" kiln, "rectangular" kiln, and "fornalha" kiln, presented in the Supplementary Material (Figure S1). Aimed at the technical and detailed understanding of the production systems, questionnaires were applied and visits were conducted in different institutions, companies, and producers in the sector. Through a bibliographic survey, information was sought on the physical and chemical properties of wood and charcoal, the particularities of each system, the operation performed manually or mechanically by employees, and average yields of carbonization products (charcoal, fines, semi-carbonized wood, pyroligneous liquid, and non-condensable gases). All charcoal production systems were based on masonry and had essential phases:

kiln loading, door closing, ignition, gas flow control, temperature monitoring, gaskets, and unloading. The flowcharts referring to the charcoal production process of each of the systems are presented in the Supplementary Material (Figures S2–S4). The encosta kiln (Figure S1A) did not have mechanized activity and was composed of two holes in the door for the entry of air and one hole in the cup for the exit of gases. During carbonization, this system was monitored through empirical knowledge of the operators from the color of the smoke and sensory aspects about the oven temperature and the elapsed time of carbonization. The rectangular kiln (Figure S1B) had the phases of loading and unloading carried out by machines and showed twenty holes for monitoring the temperature every two hours. Finally, the fornalha kiln (Figure S1C) differed from the others for mechanization in the burning of non-condensable gases and temperature monitoring using a temperature sensor. It comprised six holes along its sides for system oxygenation and temperature control. Other characteristics of the analyzed systems are presented in Table S1 of the Supplementary Material.

To select the variables investigated in the systems, through the questionnaires, information was sought regarding the physical and chemical properties of wood and charcoal and information related to the particularity of each production system, as shown in Table 1.

Table 1. Variables collected in different charcoal production systems.

Wood as Raw Material	System	Carbonization Products
Clone/Species	Capacity (m^3)	Gravimetric yield (%)
Moisture (%)	Kiln loading (h)	Ash (%)
Density (kg m^{-3})	Unloading (h)	Semi-carbonized wood (kg)
Diameter (cm)	Temperature measurement (h)	Moisture (%)
Length (m)	Ignition (h)	Density (kg m^{-3})
Input mass (kg)	Carbonization (h)	Charcoal mass on a dry basis (kg)
Higher calorific value (MJ kg^{-1})	Cooling (h)	Fines of charcoal (%)
-	Final temperature (°C)	Higher calorific value (MJ kg^{-1})
-	Machine consumption (L h^{-1})	Pyroligneous liquid (%)

Wood and labor were considered input variables of the systems. Wood was evaluated with respect to the properties that can significantly influence the energy contained in it, such as chemical composition, genetic material, moisture, and density. Labor was considered from the measurement of the time required to carry out the loading and unloading of the kilns (MJ h^{-1}). For manual activities and mechanized operations, the consumption of diesel oil (MJ h^{-1}) as well as operators' time (MJ h^{-1}) and process monitors' time (MJ h^{-1}) were obtained. Thus, the energy expenditure given by the time (h) required to perform the activity of the employees was obtained, considering that each operator consumes 2.2 MJ h^{-1} of effective work [15].

Fuel consumption for the specialized machines used in the kiln was approximately 0.33 L m^3 [16], and the employee's energy demand when operating a machine was 1.39 MJ h^{-1} [17]. The systems' output variables comprised the main products from carbonization: charcoal, fines, semi-carbonized wood, pyroligneous liquid, and non-condensable gases. The standardization of the database was carried out from the scientific literature [18–28].

The average total fines generation of 25% was adopted, distributed between 3.7% for charcoal plants, 5.8% for loading and transport, 6.3% for storage, and 9.4% for sieving. The final temperature of carbonization was standardized between 400 °C and 500 °C, and the gravimetric yield was determined through the relationship between the initial mass of wood and the final mass of charcoal.

2.2. Determination of Material and Energy Flows

The material flow of charcoal production systems was determined according to Romanelli et al. [9]. This analysis encompassed three key stages: First, the construction of a comprehensive diagram, based on the Energy Language System method, which accounted for the requisite inputs in charcoal systems. Second, the determination of material flow was achieved by directly tracking the inputs consumed in the process. Finally, the flow of materials stemming from indirectly utilized inputs was established, taking into consideration both manual and mechanized operations involved in the loading and unloading of kilns, as illustrated in Figure 1. The specialized machines used were wheel loaders with a power of 114 kW, a blade width of 2.5 m and a capacity of 2.1 m^3, and a fuel consumption of 6.88 L h^{-1} [16].

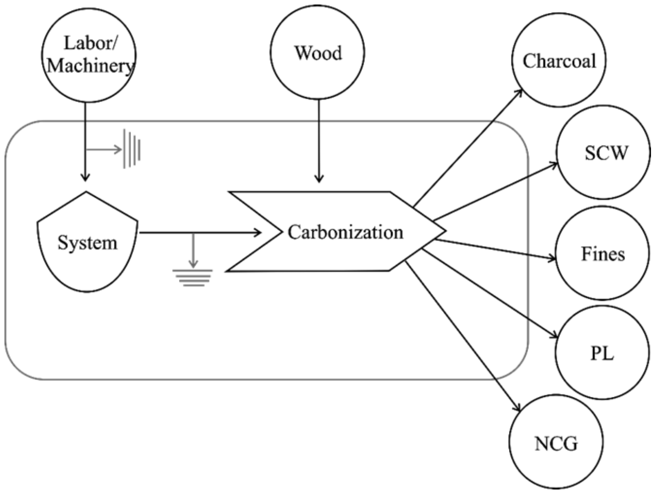

Figure 1. Material flow diagram in charcoal production. Where: SCW = semi-carbonized wood; PL = pyroligneous liquid; NCG = non-condensable gases.

After determining the material flow, the energy flow was calculated. Each material used directly and indirectly was multiplied by its respective embodied energy index (MJ $unit^{-1}$). The higher heating value, as described by Santos [29], was considered, and the useful heating value was estimated (Equation (1)) for wood, charcoal, fines, semi-carbonized wood, and pyroligneous liquid for each evaluated system. The energy contained in wood (Equation (2)) and charcoal (Equation (3)) was determined, as well as the energy contained in the systems (Equation (4)), represented by the energy expenditure of each operator and the mechanized operations of the furnace loading and charcoal unloading process.

$$\mathrm{UCV} = \mathrm{LCV} \times (100 \times \mathrm{M}/100) - 6 \times \mathrm{M} \quad (1)$$

where: UCV = useful calorific value (MJ kg^{-1}); LCV = lower calorific value (MJ kg^{-1}); 6 = conversion factor referring to energy for the evaporation of formation water; and M = moisture (%), wet basis.

$$\mathrm{ECwd} = \mathrm{UCVwd} \times \mathrm{Mwd} \quad (2)$$

ECwd = energy contained in the wood (MJ); UCVwd = useful calorific value of wood (MJ kg^{-1}); Mwd = mass of wood (kg).

$$\mathrm{ECch} = \mathrm{UCVch} \times \mathrm{Mch} \quad (3)$$

ECch = energy contained in the charcoal (MJ); UCVch = useful calorific value of charcoal (MJ kg^{-1}); Mch = mass of charcoal (kg);

$$\mathrm{ECop} = \mathrm{ECOop} \times \mathrm{Te} \quad (4)$$

ECop = energy contained in the labor of each operator (MJ); ECOop = energy consumed in each operator's labor per effective hour (MJ h^{-1}); Te = effective time to carry out the activity (h).

Mechanized operations, represented by wheel loader-type machines and the energy required for the employee to operate them, were obtained by Equation (5). The other products of the carbonization system were also accounted for in the energy flow, represented by Equations (S1)–(S4) of the supplementary material. For non-condensable gases (CO_2, CO, H_2, and CH_4), the higher calorific value was considered and the mass of the gases according to [30]. The hourly energy expenditure (MJ h^{-1}) was considered for the labor, according to [17], and for mechanized operations, according to [16]. From the determination of the energies contained in each of the products and inputs of the ovens, the energy flow of the input materials was represented by Equation (6), and the output materials by Equation (7).

$$\text{ECmec} = \text{ECOmec} \times \text{Nhe} + \text{ECop} \times \text{Te} \quad (5)$$

ECmec = energy contained in the specialized machine labor (MJ); ECOmec = energy consumed by the specialized machine per effective hour (2.2 MJ h^{-1}); Te = effective time to carry out the activity (h); ECop = energy consumed by the machine operator (1.39 MJ h^{-1}).

$$\text{IE} = \text{ECwd} + \text{ECop} \quad (6)$$

IE = input energy; ECwd = energy contained in the wood; ECop = contained energy of operators.

$$\text{OE} = \text{ECch} + \text{ECfines} + \text{ECscw} + \text{ECpl} + \text{ECncg} \quad (7)$$

OE = output energy; ECch = energy contained in charcoal; ECfines = energy contained in the fines; ECscw = energy contained in the semi-carbonized wood; ECpl = energy contained in the pyroligneous liquid; ECncg = energy contained in non-condensable gases.

The theoretical model proposed for the input and output energy flow in the three different carbonization systems is presented in Tables S2–S4 of the Supplementary Material.

2.3. Sensitivity Analysis of Carbonization Systems

The analysis and quantification of the energy flow in and out of the carbonization systems (encosta kiln, rectangular kiln, and fornalha kiln) were carried out using a parameter that relates energy available/demanded in a process known as EROI (Energy Return Over Investment) [31]. Also called "energy profitability", from the EROI, the net energy gain that each carbonization system had throughout the entire production cycle is determined [32]. For calculation, Equation (8) was taken into account.

$$\text{EROI} = \text{OE}/\text{IE} \quad (8)$$

where: EROI = return in energy on energy invested (MJ); IE = input energy (MJ); and OE = output energy (MJ).

The energy balance (E.B.) was established through the absolute energy gain per ton of charcoal produced; it refers to the net energy gain per system performed. Equation (9) was considered.

$$\text{EB} = \text{OE} - \text{IE} \quad (9)$$

where: EB = energy balance (MJ); IE = input energy (MJ); and OE = output energy (MJ).

The energy intensity (EI) was obtained per unit of product (mass and volume), being essential to evaluate processes whose products do not have the purpose of providing energy, according to Equation (10). These indicators are determined from the system's input (IE) and output (OE) energy flows.

$$\text{EI} = \text{IE}/\text{Prod} \quad (10)$$

where: EI = energy intensity (MJ m^{-3}); Prod = productivity, in m^3 ha^{-1}. The productivity adopted for wood was 300 m^3 ha^{-1}, and its respective gravimetric yield for charcoal.

The variables used to perform the sensitivity analysis of each material, such as moisture, density, oven capacity, and labor, and the respective lower and upper limits of each input material (wood and kiln) and output material (charcoal, semi-carbonized wood, fines, pyroligneous liquid, and non-condensable gases) are shown in Table S5 of the Supplementary Material. To develop the sensitivity analysis, it was necessary to simulate the behavior of each of the variables inherent to the products resulting from carbonization (charcoal, semi-carbonized wood, fines, pyroligneous liquid, and non-condensable gases) through the oscillation of each fixed percentage unit, established between the lower and upper limits of the variables, determined by the variation intervals previously presented in Table S2. A percentage oscillation of 10%, established between the lower and upper limits, was performed for all the variables shown. Subsequently, a variable was selected to be sensitized based on each system's pre-established proposed theoretical models.

3. Results and Discussion

3.1. Energy Performance of Systems

The main difference between the carbonization systems is in the percentage share of each of the carbonization products in the labor (encosta kiln and fornalha kiln) and mechanized operations (rectangular kiln). Energy input is defined as the aggregate energy embodied in all materials and processes to provide a functional charcoal unit [33]. Among the input materials in the carbonization systems, the wood had the highest participation in energy accounting, being 98%, 99%, and 98% in the encosta, rectangular, and fornalha systems, followed by the labor, 2%, 0.3%, and 2% in the encosta, rectangular and fornalha kilns, respectively, and from mechanized operations, 0.7% in the rectangular kiln (Figure 2).

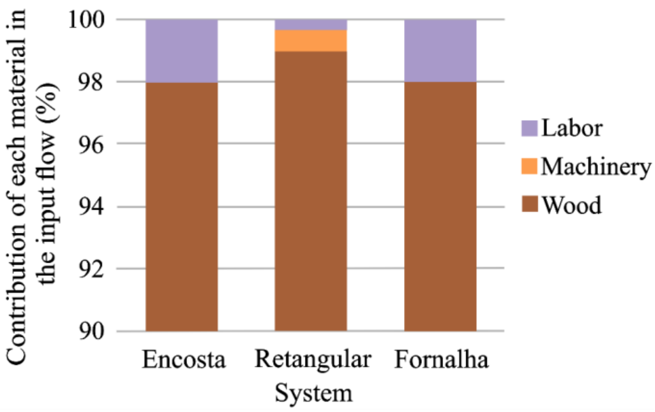

Figure 2. Energy contributions (%) of inputs in each carbonization system.

The transition from an encosta kiln or fornalha system to a rectangular kiln results in an approximate 1% increase in the amount of energy stored in the wood, simultaneously reducing the human labor component from 2% to 0.3%. This is due to the fact that the rectangular kiln system incorporates technology in the loading and unloading phases of the kiln, both before and after the carbonization process. Over the past three decades, in pursuit of greater efficiency, productivity, and charcoal quality, kilns of all categories used in wood carbonization have undergone significant and intensive modifications. The rectangular kiln systems have emerged as a result of these innovations. Although they are constructed with materials similar to those used in other types of kilns, such as solid ceramic bricks, their distinctive feature of higher volumetric capacity has allowed for the automation of the loading and unloading processes [18]. The loading process involves the introduction of raw material (wood) into the kiln before commencing the production process, followed by the unloading of charcoal after carbonization. These automated operations significantly impact the overall system's productivity and contribute to the improvement of ergonomic aspects, substantially reducing the physical effort required by the system operator, particularly when loading and unloading operations are mechanized [5].

The energy contribution contained in the carbonization output materials is shown in Figure 3.

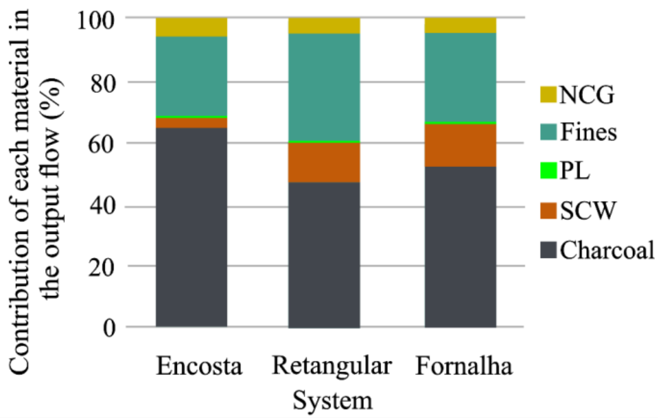

Figure 3. Energy contributions (%) of outputs in each carbonization system. Where: NCG = non-condensable gases; PL = pyroligneous liquid; SCW = semi-carbonized wood.

The largest share of energy contained in charcoal was found in the encosta kiln (65.31%), followed by the fornalha kiln (52.91%) and the rectangular kiln (47.35%). Considering that these systems are aimed at the production of charcoal, the encosta kiln is the one that provides a greater production of charcoal so that, when technology is included in these phases of operation (loading and unloading), the energy contained in this material decreases by approximately 18%, as is the case of the rectangular kiln. In this context, practical and economic considerations come to the forefront. While the hillside kiln may generate more charcoal, the automation of the rectangular kiln not only decreases the energy content of the charcoal but also enhances various practical aspects. The mechanization of operations can increase productivity, reduce the physical exertion required by operators, and optimize the overall process.

Furthermore, the rectangular kiln system reveals a significant peculiarity, with the highest percentage of energy contained in the byproducts (35.09%), followed by the fornalha kiln (29.01%) and the encosta kiln (25.68%). These byproducts play a pivotal role in the charcoal production chain [34,35], being responsible for substantial raw material losses, often exceeding 25% of the initial wood weight [36]. This is a practical aspect that requires careful consideration. Efficient management of these byproducts can not only reduce raw material losses but also have positive economic implications. The notable challenge posed by the rectangular kiln system is associated with precise temperature control, resulting in significant variability in process yield and final product quality. In this regard, operational practicality can become a determining factor. Furthermore, the need for rigorous maintenance, clay sealing, high byproduct generation rates, low yield, and an extended cooling cycle are among the disadvantages of this type of system [37]. Therefore, the decision to adopt this system should take into account not only the energy benefits but also the practical challenges involved.

The percentage of the energy contained was proportional in all analyzed systems in relation to the pyroligneous liquid. On the other hand, semi-carbonized wood had more significant participation in the fornalha kiln (13.27%), approximately four times greater than that shown by the encosta kiln (3.37%). This output material comes from the non-transformation of the raw material (wood) into the desired final product (charcoal). On a larger scale, the production of this material is directly linked to the reduction in the gravimetric yield of charcoal. In this context, it is imperative that systems be enhanced and controlled more effectively to prevent the waste of this raw material and optimize charcoal production. Once again, practical aspects, such as efficiency in transforming raw material into desired products, play a significant role in the decision-making process to meet the specific needs of charcoal production.

3.2. Sensitivity Analysis

Figure 4 presents the energy indicators of the carbonization systems investigated in this study.

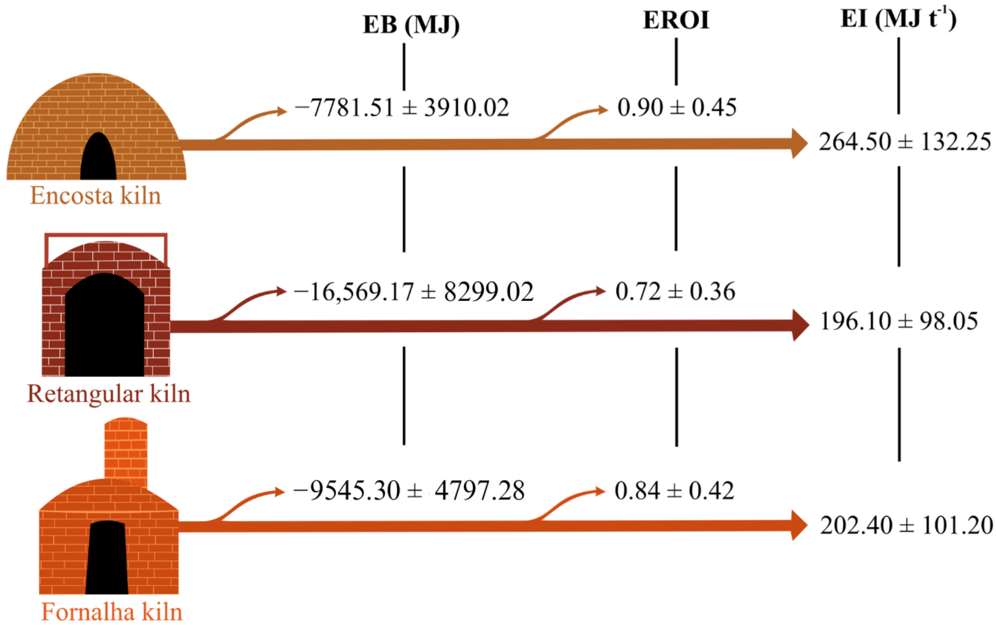

Figure 4. Energy performance indicators of carbonization systems. Where: EB = energy balance (MJ), EROI = energy profitability, EI = energy intensity (MJ t^{-1}). Means followed by the standard deviation (±).

The analysis of the energy balance in carbonization systems has revealed a consistent and challenging reality, with negative results across all cases. This finding aligns with existing references, which suggest that approximately 50% of the total energy available in the production of charcoal is irretrievably lost and cannot be recovered [38]. This underscores the inevitability of energy losses in the carbonization process, primarily in the form of heat, a situation deeply rooted in the principles of thermodynamics [39]. In accordance with the Second Law of Thermodynamics, governing both closed and open systems, any activity involving the performance of work is inherently subject to entropy [40]. Consequently, energy losses are inherent to all productive processes. It is crucial to recognize that these energy losses are a natural and inevitable part of the charcoal production landscape. All systems showed 'Energy Return on Investment—EROI' < 1, given that all energy balances were negative. In this context, it is noteworthy that the encosta kiln system showed better energy performance than the others as it had EROI closer to 01 (0.90 ± 0.45). This indicates that energy expenditure was higher than invested (output energy greater than input energy). Thus, the best energy balance (EB) response showed greater energy profitability (EROI). Comparatively, the fornalha kiln showed a similar EROI (0.84 ± 0.42) to that of the encosta kiln. Despite having a higher technical degree in the carbonization process, the rectangular kiln exhibited the lowest EROI. Regarding energy intensity (EI), despite the standardization in the simulation of the amount of charcoal produced in all kilns, the encosta kiln also showed a better performance (264.50 ± 132.25 MJ t^{-1}), followed by the fornalha kiln (202.40 ± 101.20 MJ t^{-1}) and the rectangular kiln (196.10 ± 98.05 MJ t^{-1}).

In general, although different values of energy indicators are found for other production systems, Table S3 shows how the encosta kiln system stood out in all energy performance indicators. This is because the encosta kiln makes it possible to obtain more charcoal than the others in terms of output energy (Figure 3), demonstrating that most of the energy input to the system is converted into charcoal. In addition, encosta kilns are built on sloping terrain so that most of the kiln is in direct contact with the ground and slope [41]. Thus, there is better thermal insulation, resulting in less energy loss and, consequently, greater energy efficiency of carbonization [41].

However, it is important to emphasize that energy performance, while a critical factor, should not be the sole criterion for selecting a carbonization system. In practice, widespread adoption of the inclined kiln is limited due to operational and cost-related factors. Therefore, investments in technologies that enhance the operation of inclined kilns and optimize carbonization control, such as air inlet sealing, are essential. Furthermore, a detailed analysis of the energy content (MJ) of each product and input, as presented in Table 2, can help identify the factors with the greatest impact on energy balance, energy profitability, and energy intensity, providing valuable insights for future improvements in carbonization processes.

Table 2. Inputs and outputs are used to calculate the energy in the different charcoal production systems.

Material	Indicator (MJ)	Encosta Kiln		Rectangular Kiln		Fornalha Kiln	
		LCL	UCL	LCL	UCL	LCL	UCL
Input							
Wood	ECwd	76,366.40	84,109.13	56,041.40	60,958.05	58,378.90	61,939.29
System	ECmop1	15.72	30.21	-	-	16.71	29.81
	ECmop2	4.21	8.09	1.62	2.68	4.47	7.99
	ECmop3	-	-	0.18	0.30	-	-
	ECmec	-	-	43.32	72.02	-	-
Output							
Charcoal	ECch	27,924.64	33,155.44	26,048.28	29,099.40	27,168.57	28,486.99
Fines	ECfines	19,824.58	33,479.65	8419.97	12,634.17	10,950.51	17,068.07
SCW	ECscw	8247.03	10,445.65	820.95	1970.93	5694.26	7396.16
PL	ECpl	257.37	363.39	271.17	406.47	257.07	418.43
NCG	ECncg	2474.18	3001.14	1839.41	2101.27	1893.51	1991.99

Where: LCL = lower control limit; UCL = upper control limit; ECwd = energy contained in the wood; ECmop1 = energy contained in labor needed for loading and unloading the kiln; ECmop2 = energy contained in the instrumentation; ECmop3 = energy contained in the machine operator; ECmec = energy contained in mechanized operation; ECch = energy contained in charcoal; ECfines = energy contained in the fines; ECscw = energy contained in the semi-carbonized wood; ECpl = energy contained in the pyroligneous liquid; ECncg = energy contained in non-condensable gases.

Since energy generation includes calorific value, this variable was essential to obtain the limits established in Table 2, showing different values between the other carbonization systems due to differences in the composition of charcoal [33]. The sensitized variables showed a direct and proportional relationship with the energy contained in the materials inherent to the operational procedures, such as the volumetric capacity of the system and the rate of conversion of wood into charcoal and other carbonization products.

3.3. Practical and Social Implications and Research Difficulties

Despite using several renewable energy sources in their energy matrix, developing countries, such as Brazil, still do not have thoroughly modern means to produce some of them, like charcoal. The absence of modern technologies that increase the energy efficiency of charcoal production systems and contribute significantly to reducing gas emissions (such as CO, CO_2, CH_4, and C_2H_6) during its production affects mainly small producers. Although there is already a movement to modernize production in large companies, independent producers, who still represent a significant portion of the total produced, do not have sufficient financial resources to carry out a complete modernization of their coal production units.

This reality is even more vital in populations from countries with lower purchasing power. Thus, the results presented in this study represent essential findings to guide effective public policies in these countries. Based on the knowledge of the energy performance of different production systems and the possible impact of the modernization of these systems on the energy efficiency of production, public managers can promote financial incentive programs for this action, in addition to providing technical training for qualified operators, contributing directly to the achievement of Goal 9 of the United Nations Sustainable Development Goals, which is aimed at the direct development of innovation in the countries' industries and infrastructure, inclusively and sustainably.

It was possible to observe that when the energy performance was evaluated, a traditional and low-tech system (encosta kiln) showed excellent indicators, even better than those of a system considered modern (rectangular kiln). In addition to the need to improve rectangular kilns, aiming to improve energy efficiency, this work shows an opportunity for advancement and modernization of the encosta kiln, opening the possibility for technological innovations, mainly related to process control and operation mechanization.

In addition to aspects related to innovation and modernization of the coal-producing industry, the information highlighted in this work warns about the importance of modernization to reduce the emission of greenhouse gases, such as methane. Therefore, the results contained in this work can help guide environmental public policies in developing countries. Thus, in addition to contributing to the achievement of Goal 7 (clean and affordable energy) of the Sustainable Development Goals (SDG), public policies could directly contribute to Goal 13 (action against global climate change). These goals are of great environmental relevance, and discussions frequently occur, as demonstrated in the negotiations and agreements during COP26. Although the rectangular kiln system has a low percentage of gas mitigation (2.0%), equivalent to an average reduction of 5.0 kg of methane per ton of charcoal produced, it would reduce emissions by 1575 tons per year. This is equivalent to 87,511 GJ, an electricity generation of 0.2 TWh in terms of the contained energy, thus demonstrating that these energy products can be reused with sufficient technology.

The generation of energy from clean sources is one of the global concerns in several countries. For example, Brazil has the National Energy Plan, with national targets that must be met by 2050. In this plan, the government defines aspects regarding the improvement of the national energy matrix and the decarbonization of the country's energy sources, among other elements that take into account the search for renewable alternatives that are efficient, both from the environmental point of view and from the economic point of view. Some studies in Brazil have already evaluated the possibility of using different residues in energy generation, either for direct burning or charcoal production [42]. In other words, by aligning a waste management strategy with developing technologies for transforming biomass into energy, it is possible to guarantee the energy sustainability of different countries worldwide.

In addition to being used by decision-makers in public management, the results of this work can help managers of private companies in the sense of both modernizing the company's systems and helping small producers to maximize their charcoal production and improve the energy efficiency of their production. Future studies can evaluate other charcoal production systems and, based on identifying problems, propose solutions related to the mechanization and automation of production, which can significantly improve employees' quality of life. In addition, studies that analyze these production systems' life cycle (LCA) are necessary and can substantially contribute to advances in the sustainability of charcoal production.

4. Conclusions

Despite technological, operational, and mechanization limitations, the encosta kiln system had the best energy performance in all analyzed indicators. This is because the variables "labor" and "mechanization" do not influence the gravimetric yields and, consequently, the energy performance of the carbonization process. However, such limitations directly interfere with the choice of the carbonization system. The energy performance indicators provided a theoretical basis for decision-making. Thus, the EROI must be considered a technical criterion indicating which carbonization system to use to reduce energy loss and maximize charcoal production.

It is possible to improve the charcoal production chain through investments aimed at evolving and consolidating techniques capable of guaranteeing production with more efficient energy performance directly related to controlling the carbonization process. Among these technical attributes are better thermal insulation and implementing heat recovery or combustion gas burning systems. Despite having identified a significant reduction in the emission of non-condensable gases, which directly impacts the emission of greenhouse gases, such as methane, conclusive data on the global impact of charcoal production are still lacking. Future studies can be carried out to evaluate the gas emission in each charcoal production system, with data collected directly in the kilns, which can contribute to the accurate assessment of the environmental scenario of the different technologies of charcoal production.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en16217318/s1. Figure S1. Encosta kiln (A), source: [43]; rectangular kiln (B), source: [1]; fornalha kiln (C), source: [44]. Figure S2. Flowchart of the charcoal production process in an encosta kiln. Figure S3. Flowchart of the charcoal production process in a rectangular kiln. Figure S4. Flowchart of the charcoal production process in a fornalha kiln. Table S1. Characteristics of the analyzed systems. Table S2. The theoretical model proposed for the energy input flow of the materials of the encosta kiln and the fornalha kiln. Table S3. The theoretical model proposed for the energy flow of the materials of the rectangular kiln. Table S4. Energy flow model for output materials in all types of system. Table S5. Variables used for sensitivity analysis.

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