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Biofuel in the Automotive Sector: Viability of Sugarcane Ethanol

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Abstract: In Brazil, sugarcane ethanol competes directly with gasoline as a fuel for motor vehicles, emerging as a challenging biofuel to traditional fossil fuels. The problem this article solves and presents is the Return on Energy Investment (EROI) for the production cycle of first-generation ethanol derived from sugarcane in the central-southern region of Brazil, with the main objective to compare this EROI with the gasoline marketed in Brazil, as documented in the scientific literature. The methodology for the energy analysis of the ethanol production cycle is the ratio between the energy present in a quantity of sugarcane delivered for processing and the energy consumption required for the entire process. This analysis occurs from the agricultural phase through the distribution phase of ethanol for consumption, enabling the calculation of the EROI of sugarcane ethanol and a comparative assessment with the EROI values of the gasoline marketed in Brazil. The results for EROI of sugarcane ethanol fluctuate between 8.20 and 6.52. Therefore, for each unit of energy utilized in processing ethanol, 6.52 to 8.20 units of energy are available for end use. In contrast, the EROI values for gasoline range between 2.34 and 5.50, underscoring the competitive advantage of ethanol in this context.

Keywords: sugarcane; ethanol; bioenergy; EROI

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1. Introduction

Bioethanol stands out as the most widely used non-fossil fuel in the world. The choice of raw materials to produce this biofuel depends on local conditions, generally produced from food crops, which reduces issues related to the greenhouse effect [1,2].

As described by Demirbas (2019) [1], biofuels are non-polluting, locally available, affordable, sustainable, and reliable fuels. Obtained from renewable sources, promoter supports long-term human health and ecosystem health. Biofuels offer a range of technical and environmental benefits compared to conventional fossil fuels, making them attractive alternatives for the transport sector. Among these benefits, the following stand out: reduction of greenhouse gas emissions (including reduction of carbon dioxide emissions, contributing to national and international goals), diversification of the fuel sector, biodegradability and sustainability, protection and creation of jobs, and clean energy generation.

In the context of clean energy generation, one can cite, as an example, the generation of electrical energy, generated from residues from the ethanol production process, which provides an additional market for agricultural products [3].

Currently, there is no global market for ethanol. The types of crops, agricultural practices, land and labor costs, factory sizes, processing technologies, and government policies in different regions significantly vary the costs and production prices of ethanol by region. Ethanol produced from corn in the United States is considerably more expensive than sugarcane ethanol in Brazil, and ethanol from cereals and sweet beets in Europe is even more expensive. Sugarcane ethanol, primarily produced in developing countries with warm climates, is generally much cheaper to produce than ethanol produced from cereal or sweet beet ethanol in European countries. For this reason, in countries like Brazil and India, where sugarcane is produced in substantial volumes, sugarcane-based ethanol is becoming an increasingly profitable alternative to petroleum fuels [1].

The sugarcane energy sector in Brazil presents robust, globally recognized ethanol production from sugarcane. With special emphasis on the competitiveness of sugarcane ethanol compared to gasoline, positioning it as a well-established substitute fuel for flex-fuel vehicles (flex-fuel vehicles are automobiles designed to operate with two types of fuels: gasoline and ethanol. These vehicles have engines that can automatically adjust to the fuel mixture, allowing the driver to choose to refuel with gasoline, ethanol, or a blend of both) [4].

As described by Tahir et al. (2019) [5], in Brazil, one of the reasons for the significant increase in sugarcane production after 2005 was the implementation of flex-fuel vehicle technology in the Brazilian automotive industry. This growth was positive until the 2014/2015 harvest. However, the total sugarcane production did not follow this growth due to the reduction in yield per unit area. On the other hand, successive droughts impacted all Brazilian agriculture. Mainly since 2011, water deficiency has strongly affected the productivity of sugarcane cultivation. Furthermore, the implementation of mechanized harvesting and the expansion of crops on poorer soils have also reduced productivity. The expansion of sugar cane into pastures in the central-western region of the country contributed to this decline, as the soil in this area lacks the promising quality found in traditional sugarcane regions.

On the flip side, Tahir et al. [5] describe that for the production of first-generation bioethanol, easily extractable sources of sugar or starch are used. Sugarcane has advantages: its juice contains approximately 20% sucrose and does not require a pre-treatment stage for bioethanol production, whereas corn needs to undergo a hydrolysis stage to produce sugar, which is then subjected to fermentation. Sugarcane and corn are the two main crops used for first-generation bioethanol production, accounting for over 80% of the total bioethanol biofuel worldwide. However, the widespread adoption of first-generation biofuels from cereals is considered questionable due to the perception that such crops compete with food production and may have a negative impact on food prices. Additionally, land requirements for these crops, such as corn, also present a challenging situation. The average bioethanol production capacity of sugarcane is 7500–8000 $L \cdot ha^{-1}$, while that of corn is 3460–4020 $L \cdot ha^{-1}$. Thus, to produce the same amount of bioethanol, corn requires twice as much land as sugarcane.

The ethanol production process allows for the generation of this biofuel in two forms: hydrated ethanol and anhydrous ethanol. In Brazil, hydrated ethanol is sold at consumer points for final use in combustion engines, while anhydrous ethanol is sold at distributors and added to gasoline. In other words, all gasoline marketed in Brazil, for vehicular use, is blended with anhydrous ethanol at a ratio of 27% by volume [6].

The study conducted by Ternel et al. (2021) [7] demonstrates that both standard and advanced biofuels (liquid and gaseous) constitute a highly efficient means of rapidly reducing greenhouse gas emissions from the global vehicle fleet without significant adjustments to powertrains and service stations across Europe. Increasing the incorporation rate of biofuels would yield immediate results, and advanced biofuels or BIOCNG can sidestep the biofuels controversy regarding competition with arable land intended for food production. Substantial investments are required to develop advanced biofuel production, considering all value chains.

However, in Brazil, the popularity of flex-fuel vehicles stands out. These vehicles are designed to operate on different proportions of gasoline and hydrated ethanol, allowing drivers to choose the most cost-effective fuel at the time of refueling. In November 2023, flex-fuel vehicles represented 82% of the light vehicle fleet in Brazil, while gasoline vehicles accounted for a percentage of 3.3%, confirming the competitiveness of ethanol compared to gasoline. One of the main reasons for the success of this type of engine, used by major vehicle manufacturers in Brazil, is the abundance of sugarcane in the country. Sugarcane is the primary raw material for ethanol production, presenting itself as a cleaner and renewable alternative compared to gasoline. On the other hand, the benefits of flex-fuel vehicles include reducing dependence on fossil fuels, decreasing greenhouse gas emissions and promoting a more sustainable energy matrix. In Figure 1, the demand for Flex vehicles in Brazil from 2019 to 2023 in comparison to gasoline can be observed [8], which demonstrates the consolidated market for this type of vehicle in Brazil.

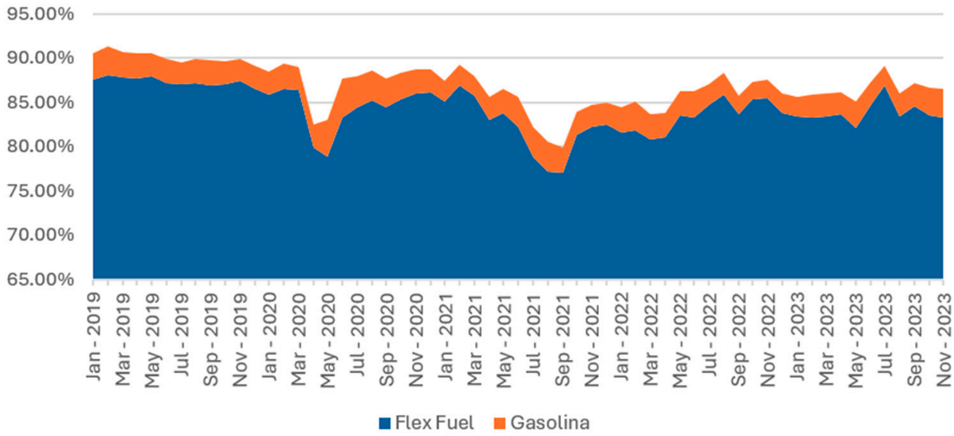

Figure 1. Demand for flex vehicles in Brazil in comparison to gasoline.

The sugarcane ethanol production process in Brazil occurs through sugarcane milling or by diffusion, but the predominant process in the country is milling, and both processes are characterized by generating a large amount of residue, called sugarcane bagasse. This residue becomes fuel for the boilers to generate steam, which in turn produces thermal energy in the form of steam and the subsequent production of mechanical and/or electrical energy in steam turbines. This amount of thermal and electrical energy is sufficient to meet the needs of the ethanol-producing plant and sell excess electrical energy to the distribution network. In this way, the use of sugarcane bagasse for cogeneration of energy is the reason why the energy balance of the production of ethanol from sugarcane is highly positive since no fossil fuel is used, except those that are included in the fertilizers and pesticides, in addition to diesel oil used in agricultural equipment and in transporting sugarcane to supply the distilleries, as well as in transporting ethanol from the plant to distributors and from distributors to points of consumption [9–13].

Thus, the sugar-energy sector stands out for its use of waste generated, adding energy value to the ethanol production flow, which makes it possible to maximize natural resources and generate new energy products that add energy value to the sector's production flow.

The overall content of this article aims to demonstrate the energy efficiency of first-generation sugarcane ethanol (1G) produced in autonomous distilleries in Brazil using the Energy Return on Investment (EROI). Additionally, it seeks to compare the obtained value for this energy indicator with the EROI of gasoline produced and marketed in Brazil, according to the data available in conducted studies. This comparison will thereby validate the energy sustainability of 1G ethanol.

2. Methodology

The methodology used in this article involves measuring energy flows within the ethanol production process and evaluating energy consumption at each stage of production. This measurement is performed using regression analysis, which is categorized into three levels.

For the agricultural stage (AS), level 1 refers to the energy consumed through fuels used in the processes of agricultural operations and transport of sugarcane from the cane fields to the mill. Level 2 of regression for AS refers to the energy contained in the agricultural inputs used, that is, fertilizers, limestone, herbicides, insecticides, and seedlings, and level 3 of regression for AS portrays the energy for construction and maintenance of necessary equipment and buildings.

For the industrial stage (IS), level 1 deals with the consumption of electrical, mechanical, and thermal energy to be used in the plant. For the IS, level 2 portrays the energy contained in the inputs necessary to be used in the industrial process, that is, sodium hydroxide, lime, sulfuric acid, cyclohexane, antifoam, lubricants, and other necessary inputs. Regression level 3 for the IS portrays the energy for the construction and maintenance of necessary equipment and buildings.

Likewise, in the distribution stage (DS), level 1 portrays the energy consumed through fuels for transportation operations, which include transporting ethanol from the producing plant to the fuel distributor and then to resellers and/or supply points. For the distribution stage, level 2 presents the energy contained in tires and lubricants. Finally, regression level 3 for DS portrays the energy for construction and maintenance of necessary equipment and buildings.

The addition of subsequent levels, such as the fourth and fifth level, are not included in this article, due to the lack of robust information, as well as a significant increase in information. These regression levels refer to the energy embodied in supporting work and other economic services, therefore, in this work, energy flows were considered only up to the third level of regression [3,12,13], as can be seen in Figure 2.

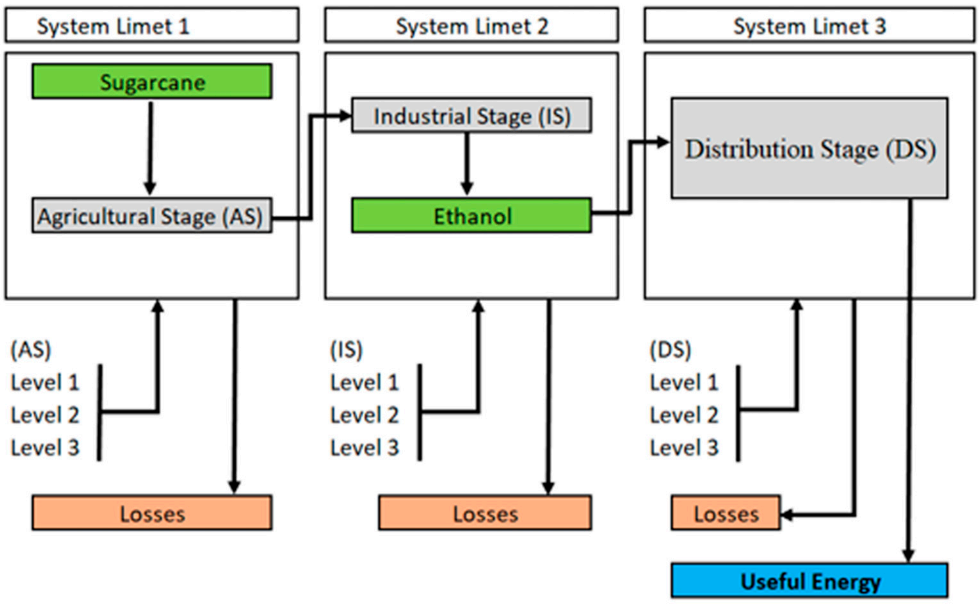

Figure 2. Energy flow accounted for in the ethanol production flow.

The energy accounting format for the sugarcane ethanol production flow considers an approach from the production of the raw material to the availability of the product to the final consumer (Well-To-Tank).

This type of approach implies some steps to be followed for energy accounting:

(a) Survey and validate sugarcane productivity data; (b) measure the energy available in sugarcane as a function of productivity; (c) measure the energy consumption of the process by regression level; and (d) determine the EROI in the sugarcane ethanol production flow. Finally, a comparison will be made between the EROI of incoming Ethanol and the EROI of gasoline, available in the sector literature.

3. Survey and Validation of Sugarcane Productivity Data

The collected and consolidated data refer to the productivity per harvest of sugarcane crops in Brazil from 2007/2008 to 2021/2022, as per information available on the Conab website (https://www.conab.gov.br/info-agro/safras/cana (accessed on 16 June 2021)). As can be observed in Figure 3, throughout the period analyzed, sugarcane productivity in tons of cane per hectare (tc/ha) varied between 110.10 tc/ha and 63.15 tc/ha, with an average value production of 77.23 tc/ha, this variability can be attributed to the age of the sugarcane field. It should be emphasized that the sugarcane crop productivity data provided by Conab does not mention the planting method for the first harvest, whether it is an 18-month plant cane or a 12-month plant cane. Therefore, in this article, it is considered that the productivity data in tons of sugarcane per hectare per year (tc/ha·year) are equivalent to the productivity data in tons of sugarcane per hectare (tc/ha), and that each crop involves a total of six harvests.

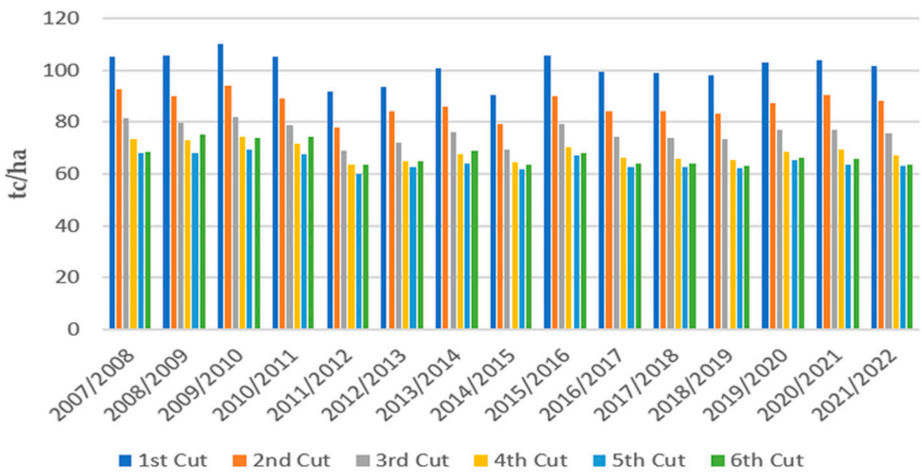

Figure 3. Productivity per harvest of sugarcane crops in Brazil from 2007/2008 to 2021/2022.

In addition to Figure 3, Table 1 presents the maximum and minimum productivity values per cut, as well as the percentages of sucrose, fiber, and straw considered in this work.

Table 1. Data survey.

Sugarcane Productivity Data Per Cut							
Cut	**1st**	**2nd**	**3rd**	**4th**	**5th**	**6th**	**Average**
Maximum (tc/ha)	110.10	94.10	82.10	74.40	69.50	75.20	84.23
Minimum (tc/ha)	90.37	78.01	68.69	63.70	59.73	63.15	70.61
Average (tc/ha)	100.86	86.72	75.88	68.33	64.48	67.10	77.23

Sugarcane Components			
Limits	**% Sucrose**	**% Fiber**	**% Straw**
Maximum	17.00	14.00	14.00
Minimum	10.00	8.00	14.00
Average	14.75	12.05	14.00

Sugarcane is a plant that generally supports six cuts, and its composition is an inherent variable in the production process and susceptible to the season of the year, showing changes from one season to another. The potential of sugarcane residues in terms of dry matter is around 14% of the mass of the stem, which means that for each ton of stems, there are 140 kg of dry residues. Experiments carried out show a significant difference that can be observed between the average value of 14% and an average value of 18.2%. However, this can be explained mainly by differences in methodology and experiments that do not consider the effect of moisture content and the cutting stage, as well as the differences between the varieties considered [14]. Regarding the amount of water available in sugarcane, this value can vary between 65% and 75% [15,16]. In addition to Figure 3,

Table 1 presents the maximum and minimum productivity values per cut, as well as the percentages of sucrose, fiber, and straw considered in this work.

Validation of the collected data includes checking the consistency of the data, this verification occurred through the calculation of the coefficient of variation (CV) and the variation index (IV). The coefficient of variation (CV) is determined through the ratio between the standard deviation (s) and the average $(\bar{x})$, in percentage, based on the sample size, demonstrating the size of the measurements. The variation index (IV) is determined through the ratio between the variation coefficient (CV) and the square root of the number of repetitions (n) of the experiment. The variation index considers the number of measurements for the period under analysis, which demonstrates that the lower this index, the more accurate the data collected. However, it is worth highlighting that in Brazil the sugar-energy market does not have a coefficient of variation analysis for the different types sugarcane cultivars, requiring the use of generic parameters used in different types of crops [3,17]. The calculation format for the coefficient of variation (CV) and the variation index (IV) can be observed in Equations (1) and (2), respectively.

$$CV = \left(\frac{s}{\bar{x}}\right) \times 100 \tag{1}$$

$$IV = \frac{CV}{\sqrt[2]{n}} \tag{2}$$

Validation of the data through analysis using the coefficient of variation demonstrates that the collected data have a high level of precision, as can be seen in Table 2.

Table 2. Coefficient of Variation Analysis.

Cut	Number Repetitions	Average (tc/ha)	Standard Deviation (tc/ha)	*CV* (%)	*IV* (%)	Level Accuracy
1st cut	15	100.86	5.61	5.56	1.44	High
2nd cut	15	86.72	4.60	5.31	1.37	High
3rd cut	15	75.88	4.01	5.29	1.36	High
4th cut	15	68.33	3.45	5.05	1.30	High
5th cut	15	64.48	2.88	4.46	1.15	High
6th cut	15	67.10	4.20	6.26	1.62	High

CV: Coefficient of variation; *IV*: Variation index; Sample Size: 90; Number of repetitions: 15.

4. Energy Available in Sugarcane as a Function of Productivity

The genetic improvement of sugarcane destined to produce sugar promoted the obtaining of genetic materials with high production of sucrose in the juice; in this way, when all the energy contained in the sugars and in the fibers is transformed into the same unit, the energy of sugarcane is around 7400 Megajoule per ton of clean stalks (MJ/tc) [18,19].

The amount of sugarcane primary energy per clean stem is directly related to its components: sucrose, fibers from thatch, and straw. As a result, the primary energy available per ton of clean sugarcane stalk is as follows: 2500 MJ/tc for sucrose, 2400 MJ/tc for stalk fibers, and 2500 MJ/tc for straw. The mass ratio kg/tc for sucrose, culm, and straw fibers are 150, 135, and 140, respectively [9,18].

The amount of energy delivered per cut by sugarcane (Esc) can be determined by the ratio between sugarcane productivity per cut (Pi) and the average per cut (Ai), multiplied by the amount of primary energy available in each component of sugarcane, 7400 MJ/tc for sugar cane [3]. As can be observed in Equation (3). However, the amount of energy available in the components of sugar cane, considering only sucrose (Ees) or fiber (Eef), can be observed in Equations (4) and (5), respectively.

$$Esc = \frac{Pi \times 7400}{Ai} \quad (3)$$

$$Ees = \frac{Pi \times 2500}{Ai} \quad (4)$$

$$Eef = \frac{Pi \times 2400}{Ai} \quad (5)$$

Sugarcane is a semi-perennial crop, as after planting, it is cut several times before being replanted. Its production cycle is, on average, six years with five cuts. The appropriate choice of planting time is essential for the good development of the sugarcane crop, which requires ideal climatic conditions to develop and accumulate sugar. For its growth, sugarcane needs high water availability, high temperatures, and a high level of solar radiation. The most important characteristics of sugar cane for the ethanol and electricity production process are the sugar and fiber content. The composition of sugarcane varies depending on the variety of sugarcane cultivars, soil, climate, water availability, and harvest time, among other aspects.

The amount of total available energy delivered by sugarcane for the sample under study can be observed in Table 3.

Table 3. The energy available in sugarcane.

Energy in Sugarcane (MJ/tc)							
	1st cut	**2nd cut**	**3rd cut**	**4th cut**	**5th cut**	**6th cut**	**Average**
Maximum	8078.10	8029.41	8006.46	8057.38	7976.46	8293.04	8073.48
Minimum	6630.50	6656.48	6698.71	6898.59	6855.17	6964.07	6783.96
Average	7354.30	7342.94	7352.59	7477.98	7415.82	7628.56	7428.70
Sucrose (MJ/tc)							
	1st cut	**2nd cut**	**3rd cut**	**4th cut**	**5th cut**	**6th cut**	**Average**
Maximum	2729.09	2712.64	2704.89	2722.09	2694.75	2801.70	2727.09
Minimum	2240.03	2248.81	2263.08	2330.60	2315.94	2352.73	2291.86
Average	2484.56	2480.72	2483.98	2526.35	2505.34	2577.22	2509.70
Fiber (MJ/tc)							
	1st cut	**2nd cut**	**3rd cut**	**4th cut**	**5th cut**	**6th cut**	**Average**
Maximum	2619.92	2604.13	2596.69	2613.20	2586.96	2689.63	2618.42
Minimum	2150.43	2158.86	2172.55	2237.38	2223.30	2258.62	2200.19
Average	2385.18	2381.50	2384.62	2425.29	2405.13	2474.13	2409.31

The average values of energy delivered per ton of sugarcane presented in studies already carried out are within the maximum and minimum limits presented in this article and very close to the calculated averages, which presents robustness in the data obtained. However, it should be noted that for straw, this article considers that 100% of the straw remains in the field.

5. Measurement of the Energy Consumption of the Production Process by Regression Level

In this section of this article, measurements of energy consumption for each stage of production of sugarcane ethanol will be presented by level of regression.

5.1. Energy Consumption in the Agricultural Stage

During the agricultural stage, the practices used may vary according to regional characteristics, such as soil, water availability, and soil inclination, among other factors influencing the management to be adopted. In Figure 4, the process flow of the agricultural stage can be seen in a simplified way [3].

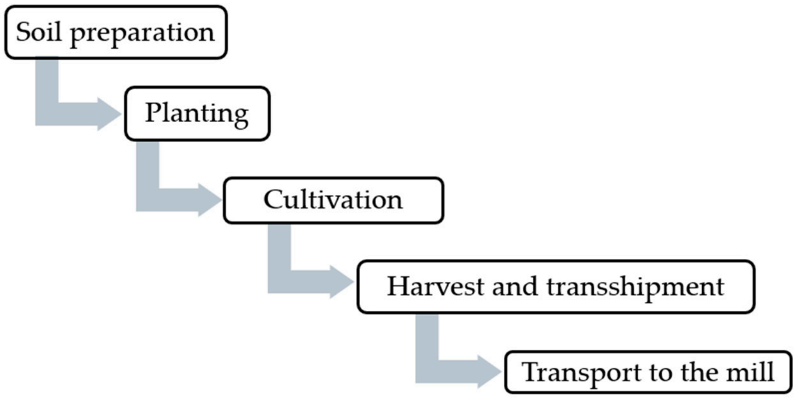

Figure 4. Agricultural stage process flow.

The energy consumption in the agricultural stage is represented in regression levels. Each regression level is associated with a specific quantity of agricultural activities directly linked to energy consumption, as can be observed in Table 4 [3].

Table 4. Energy consumption in the agricultural stage—Regression levels.

Regression Level	Activities
Level 1a—Fuels used	Planting, cultivation, and cultural treatment.
	Mechanized Harvest.
	Transshipment and transport in the sugarcane field.
	Transport from the sugarcane field to the mill.
Level 2a—Other inputs	Application of fertilizers, limestone, herbicides, and insecticides.
Level 3a—Energy for production and maintenance	Production, maintenance, and labor used with the equipment.

5.1.1. Energy Consumption Level 1a—Agricultural Stage

Planting and cultivation activities are characterized by the use of equipment with diesel engines with a power between 170 hp and 69 hp [15].

As described by De Figueiredo; La Scala (2012) [20], diesel consumption for plant cane and ratoon cane activities represents 124.20 L/ha and 11.35 L/ha, respectively.

Analogously, Bordonal (2013) [21] describes that the diesel consumption for plant cane and ratoon cane activities are 166.73 L/ha and 20.36 L/ha, respectively.

It is worth mentioning that the use of equipment during cultivation, planting, and cultural practices is not used in 100% of the sugarcane fields. However, in this article, the diesel consumption values considered follow those described by Macedo et al. (2004) [15], where it was possible to identify the consumption of diesel for planting, cultivation, and cultural treatment activities, for the plant cane phase of 125.52 L/ha and the ratoon cane phase of 33.81 L/ha.

In this context, the consumption of diesel related to the application of vinasse is characterized by using trucks, a sprinkler system, and, in combination, a truck and a sprinkler system for the consumption of diesel related to the application of filter cake and transport of seedlings, this is characterized by through the use of trucks. Thus, diesel consumption for the application of vinasse in the cane ratoon phase is 24.68 L/ha, for the application of filter cake in the cane plant phase, diesel consumption is shown at 9.60 L/ha, for transporting sugarcane seedlings, diesel consumption is 17.39 L/ha.

The calculation of the energy consumption for the activity of planting, cultivation, and cultural treatment (*ECAS1a*) was carried out considering the productivity per sugarcane cut (Pi) and the consumption of diesel during this activity (L), as well as the density (d) and the lower calorific value (LHV) of diesel, as can be observed in Equation (6); therefore, the energy consumption for this activity is between 44.53 MJ/tc and 17.34 MJ/tc [3].

$$ECAS1a = \frac{d \cdot LHV \cdot L}{Pi} \tag{6}$$

In Brazil, the mechanized harvesting activity has advanced a lot in recent years. The energy consumption in the mechanized harvesting activity refers to the consumption of diesel carried out with the sugarcane harvesters. This consumption can present some variations, and these variations occur in the function of the terrain, way of operating, and route to be followed, among other variations.

Marques (2019) [3] describes that the average consumption of diesel for this equipment, through an analysis of 16 samples presented by some researchers, that the average consumption of diesel for the mechanized harvesting activity is 82.00 L/ha [10,15,20–25].

The calculation of energy consumption for the mechanized harvesting activity was carried out in a similar way to that carried out for the planting, cultivation, and cultural treatment activity. Based on the data presented, the energy consumption for the mechanized harvesting activity is between 29.09 MJ/tc and 42.06 MJ/tc.

For transshipment and transport activities in the sugarcane field, the total consumption of diesel for transshipment and transport activities in the sugarcane field is 39.88 L per hectare, with an average consumption of 14.24 L per hectare for the transshipment and 25.63 L per hectare for transport activity in the sugarcane field. Energy consumption was determined using the same parameters considered in planting, cultivation, cultural practices, and mechanized harvesting activities. The results found are between 14.15 MJ/tc and 20.46 MJ/tc [3,15,20,22].

The completion of energy accounting from the agricultural stage to Level 1a occurs with the transport of harvested sugarcane to the plants. In Brazil, transport from the sugarcane field to the plant occurs by road. In general, the distances between the sugarcane field and the plant are around 20 km, and the diesel consumption for the equipment (or trucks) used is between 1.15 km/L and 2.2 km/L. This equipment has a load capacity between 15 and 45 tons of sugarcane (tc), with a factor utilization of 8% (*FU*). The calculation of energy consumption related to the transportation activity from the sugarcane field to the plant (*ECAS1.1a*) is related to fuel consumption (C), distance traveled between the sugarcane field and the plant (Dist), equipment load capacity load (*Cap.*) and factor utilization (*FU*), density (*d*), and lower calorific value of diesel (*LHV*). As can be seen in Equation (7), energy consumption in this activity is 29.51 MJ/tc. Thus, energy consumption for Agricultural Stage Level 1a is between 114.71 MJ/tc and 101.12 MJ/tc [3].

$$ECAS1.1a = d \cdot LHV \cdot \frac{1}{C} \cdot 2 \cdot Dist \cdot \frac{1}{Cap} \cdot FU \tag{7}$$

5.1.2. Energy Consumption Level 2a—Agricultural Stage

The energy consumption referring to level 2a is the energy embedded in the inputs used during the agricultural stage, such as fertilizers, limestone, herbicides, and insecticides. Energy consumption in this phase is characterized by the amount of nutrients and limestone applied to the cane field. The calculation of energy consumption at this level (*ECAS2a*) was performed based on the application rate of each nutrient (*Nu*) in kg/ha and the energy embedded in each nutrient (*ENu*) in MJ/kg, as well as the productivity of the sugarcane field per cut (Pi), as can be observed in Equation (8). Thus, for level 2a of the agricultural stage, energy consumption is between 113.43 MJ/tc and 95.69 MJ/tc [3,15].

$$ECAS2a = \frac{Nu \cdot ENu}{Pi} \tag{8}$$

5.1.3. Energy Consumption Level 3a—Agricultural Stage

The energy consumption related to level 3a is the total energy used in the production, maintenance, and labor of the equipment involved (*ECAS3a*). This energy consumption should be calculated based on the following factors: total energy consumed in the production, maintenance, and labor of the equipment used (*Ete*); equipment's useful life (*Vu*); and productivity per harvest (*Pi*), as observed in Equation (9). The energy consumed at this level presents an average variation between 28.98 MJ/tc and 24.40 MJ/tc [3,10,15].

$$ECAS3a = \frac{\frac{Ete}{Vu}}{Pi} \tag{9}$$

5.1.4. Total Energy Consumption—Agricultural Stage

The total energy consumption in the agricultural stage is presented by means of the sum of the energy consumed in levels 1a, 2a, and 3a. Table 5 presents energy consumption for these three levels of regression of the agricultural stage.

Table 5. Energy consumption in the agricultural stage.

Cut		**1st (MJ/tc)**	**2nd (MJ/tc)**	**3rd (MJ/tc)**	**4th (MJ/tc)**	**5th (MJ/tc)**	**6th (MJ/tc)**	**Average (MJ/tc)**
Level 1a	Max.	125.91	99.79	109.32	115.58	121.30	116.33	141.71
	Min.	108.64	87.77	96.29	103.20	108.39	102.42	101.12
Level 2a	Max.	43.20	108.00	122.66	132.27	141.06	133.42	113.43
	Min.	35.46	89.54	102.62	113.25	121.23	112.04	95.69
Level 3a	Max.	22.19	25.70	29.19	31.47	33.57	31.75	28.98
	Min.	18.21	21.31	24.42	26.95	28.85	26.66	24.40
Total	Max.	191.30	233.49	261.17	279.32	295.92	281.50	257.12
	Min.	162.30	198.62	223.33	243.39	258.47	241.12	221.21
	average energy consumption: 239.16 MJ/tc							

5.1.5. Energy Consumption and Losses—Agricultural Stage

Sugarcane provides a total of energy between 8074.48 MJ/tc and 6783.92 MJ/tc when it is available to be harvested. The straw left in the field, resulting from the mechanized harvesting process itself, represents values between 2727.53 MJ/tc and 2291.86 MJ/tc. Thus, an amount of energy between 5345.95 MJ/tc and 4492.05 MJ/tc is available for the agricultural stage, including sucrose, and fiber.

The average specific losses in the agricultural stage are 6.25% [3,23,26,27] and occur during the mechanized harvesting activity. Thus the amount of energy lost, referring to the raw material delivered by the sugarcane, is between 334.12 MJ/tc and 280.75 MJ/tc for the agricultural stage.

5.2. Energy Consumption in the Industrial Stage

The detailing of the ethanol production flow, as well as energy consumption, is associated with the type of plant that will process sugarcane. There are three main types of sugar and ethanol-producing plants from sugarcane in Brazil: sugar-producing plants, autonomous distilleries to produce only ethanol, and integrated plants for the joint production of sugar and ethanol. The configuration of the production plant directly implies the flow of ethanol production and energy consumption, specifically in the industrial stage. It should be noted that this article will only address the autonomous distilleries.

The industrial stage of ethanol production in an autonomous distillery comprises the following phases: cleaning, preparation, and milling; juice treatment; concentration of juice; sterilization and wort cooling; fermentation; distillation and rectification; and dehydration and cogeneration of energy. In Figure 5, the industrial stage in an autonomous distillery is highlighted. A point of evidence in the industrial stage is that all the energy, steam, and electricity needed in this production process is produced by the plant using sugarcane bagasse as fuel. In many plants, the excess electricity generated is commercialized, being sold to the grid. Some mills recover sugarcane straw and use it as fuel, but this is still not a common practice in Brazilian facilities due to high recovery costs and short and long-term implications. However, the elimination of sugarcane burning provides an opportunity for the use of straw. In this work, the permanence of straw in the field after harvest is considered [3,28].

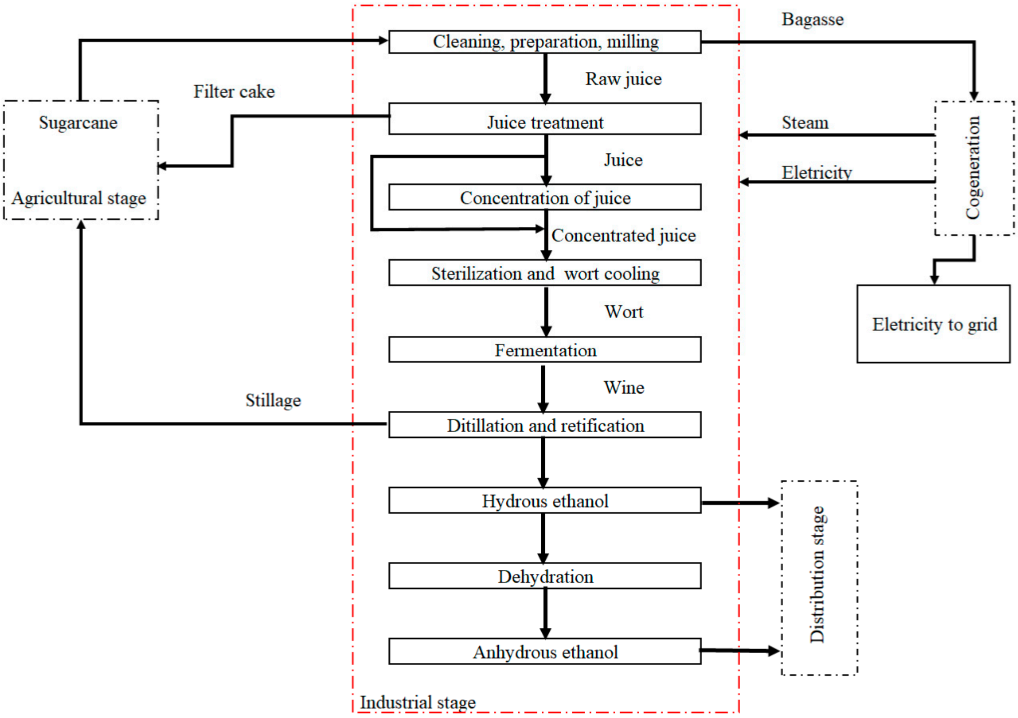

Figure 5. Block diagram—Autonomous distillery—Industrial stage.

For the industrial sector, the cleaning process consists of unloading and dry cleaning the chopped sugarcane. The preparation process consists of breaking up the cells of the chopped cane to increase the recovery of sugars in the extraction stage. This breaking occurs by means of levelers, choppers, and shredders, made up of knives and rotary hammers, whose objective is to standardize the material for the next process, extraction or milling. The objective of the extraction or milling process is to separate the juice containing sucrose from the rest of the cane, which is mainly composed of fiber. In Brazil, this extraction process generally takes place by means of four to six sets of mills in an extraction unit, and soaking water is used to increase the extraction of sugars [3,9,29–31].

The juice treatment process consists of removing the impurities contained in the juice, in the first phase of the treatment the removal of impurities occurs through sieves to remove insoluble solids (sand, clay, etc.). The second phase refers to the chemical treatment for the removal of insoluble impurities, promoting the coagulation, flocculation, and precipitation of these impurities, which are eliminated by sedimentation. The chemical treatment takes place by adding milk of lime, heating using steam, and decanting through polymers, resulting in clarified juice and sludge, after filtering the sludge through rotating centrifuges, a residue called filter cake is obtained, which is of the order of 30 to 40 kg per ton of sugarcane, which is used in the fertirrigation process in the sugarcane plantation. On the other hand, the liquid resulting from the filtration returns to the beginning of the juice treatment process [3,32].

The clarified juice is concentrated in evaporators, different types of evaporators can be used, that is, single effect or multiple effect evaporators. The clarified broth has a concentration of 14° to 16° Brix and is concentrated between 55° to 65° Brix in the evaporators. Juice concentration for syrup production and storage is one of the treatment operations, which fits as a procedure for raising the total sugar content of the must and raising the alcohol content, which guarantees the continuity of the fermentation process in stops of fermentation. However, for syrup storage, the concentration should be as high as possible, reaching a limit close to the crystallization critical limit [3,30,33].

The process of sterilization and cooling of the wort consists of heating the clarified juice and the concentrated juice up to 130 °C and cooling to a temperature of 32 °C, suitable for the fermentation process [28,31]. After sterilization and cooling of the wort, the fermentation process takes place, in Brazil the fermentation process most used in distilleries to obtain ethanol is the Melle-Boinot process. This process is characterized by the recovery of the yeast through centrifugation of the wine, which allows reuse in subsequent fermentations. The fermentation vat feeding time is between four and five hours. When the vat is fed with the wort, the fermentation process begins, which consists of converting all the sugars present in the wort into alcohol and by-products, in general. The time taken for the complete process is four to seven hours. The final product of this process is the fermented wine, which is centrifuged to separate the yeast.

In the distillation process, the centrifugated fermented wine is purified, with a content of 7% to 10% ethanol by mass. The most frequent configuration of the alcoholic distillation process used in the sugar and alcohol sector in Brazil occurs through distillation columns and rectification columns. In the distillation columns, purified wine is obtained, and in the rectification columns, hydrated ethanol is obtained, with an ethanol content between 92.6 and 93.8% by mass [30,34].

As described by Bereche (2011) [35], anhydrous ethanol is obtained through the dehydration process. In Brazil, the main dehydration methods used in the sugar and alcohol sector are heterogeneous azeotropic distillation with cyclohexane, homogeneous azeotropic distillation with mono ethylene glycol (MEG), and adsorption on molecular sieves. The process to be considered in this article refers to homogeneous azeotropic distillation with monoethylene glycol (MEG). In this process, a column is used in which the desiccant is fed from the top and the hydrated ethanol is dehydrated in the vapor phase. The MEG desiccant absorbs and draws water to the base of the column, and the anhydrous ethanol vapors exit through the top, where the ethanol is condensed and sent for storage in the reservoirs. The mixture containing water, MEG, and a small amount of ethanol is sent to a recovery column, from where the MEG solvent returns to the dehydration process [31,36].

The energy consumed in the industrial stage is presented as a function of the sum of energy consumption in three levels of regression: (a) Level 1i—Energy required for the ethanol production process; (b) Level 2i—Energy embedded in the necessary inputs for ethanol production; and (c) Level 3i—Energy required for the construction of buildings and industrial equipment, as well as the maintenance of the equipment involved.

5.2.1. Energy Consumption Level 1i—Industrial Stage

To determine energy consumption for level 1i, an autonomous distiller plant with a processing capacity of 2,000,000 tc/year was adopted with the operating parameters: milling capacity of 500 tc/h, 4000 h/year of operation per harvest [37]. This operational condition presented represents a production of 80.4 L/tc of anhydrous ethanol with a degree of purity of 99.4% and 85.47 L/tc of hydrous ethanol, with a degree of purity of 93.5% [28].

The consumption of steam to meet this demand can be seen in Table 6, meeting the needs of the process for the production of anhydrous ethanol and hydrous ethanol with low-pressure steam demand, 2.5 bar and 6.0 bar, commonly used [28]. The determination of enthalpy values is obtained through tables of thermodynamic properties of saturated water [38]. The calculation of the thermal energy consumed is obtained by the product between the steam consumption and the enthalpy difference, that is the difference between the enthalpy of the saturated steam and the enthalpy of the saturated liquid.

Table 6. Consumption of steam and thermal energy—Level 1i.

Process	Steam Pressure (bar)	Enthalpy Δh [1] (MJ/kg Steam)	Steam Consumption (kg steam/tc)		Thermal Energy Consumed (MJ/tc)	
			Hydrous Ethanol	Anhydrous Ethanol	Hydrous Ethanol	Anhydrous Ethanol
Juice sterilization	6	2.09	51.20	51.20	106.78	106.78
Dehydration in extractive column			-	24.80	-	51.72
Dehydration in recovery column			-	8.60	-	17.94
Evaporation System	2.5	2.18	164.20	164.20	358.20	358.20
Distillation column A			147.00	147.00	320.68	320.68
Distillation column B-B1			71.90	71.90	156.85	156.85
Total			434.30	467.70	942.51	1012.18

[1] Δh—Difference between enthalpy of saturated steam and enthalpy of saturated liquid.

The electricity demand of an autonomous distiller plant depends mainly on the milling capacity, but also on mechanically driven turbines or electric motors for larger loads, to drive the equipment involved. Typical autonomous distilleries plant in South Africa have specific electricity demands of between 21 kWh/tc to 22 kWh/tc when using mechanically driven turbines. However, with the use of fully electric drives this demand changes to 29 kWh/tc to 31 kWh/tc [29]. However, using only electrical equipment, the specific electricity consumption is around 28 kWh/tc [39].

In Brazil, values commonly used for energy consumption are around 28 kWh/tc, which are divided into 16 kWh/tc, necessary for the mechanical energy demand for the broth preparation and extraction system, and 12 kWh/tc, necessary for the electricity demand of the ethanol production process [28,37,40,41].

To meet the operational demand of an autonomous plant, similar to the one used in this article, energy consumption is 28 kWh/tc or 100.80 MJ/tc to meet the production process, and the amount of surplus electricity is 57.90 kWh/tc or 208.44 MJ/tc, so the amount of electricity generated represents a total of 85.90 kWh/tc or 309.24 MJ/tc [28,42]. It should be noted that for a cogeneration system based on a steam cycle with backpressure turbines, with technological characteristics of pressure and temperature, the amount of steam generated in the boiler is necessary to meet the needs of the process. In this way, when the steam consumption in the process is low, the amount of bagasse available for the cogeneration process increases. However, for thermally integrated cases, the surplus of electricity is smaller due to the smaller amount of steam that passes through the turbines [24].

The losses related to the steam generated by the boilers, it is in the order of 4% [33], however, this percentage of loss can reach the value of 5% [34]. So, for this study, the value considered for the loss of steam is 5%. Therefore, considering the steam losses that occurred in the process in the order of 5%, for the production of hydrated ethanol, 456.02 kg of steam/tc of live steam is needed, and for anhydrous ethanol, the amount of live steam needed is 491.09 kg of steam/tc, so this steam loss value represents a thermal energy loss of 47.13 MJ/tc for hydrated ethanol and 50.61 MJ/tc for anhydrous ethanol. With the knowledge of the amount of steam consumption, thermal energy, electricity demand, and relative losses in steam generation, it becomes possible to determine the energy consumption for Level 1i of the industrial stage, as can be seen in Table 7.

Table 7. Energy consumed—Industrial stage level 1i.

Energy Consumed	Hydrous Ethanol	Anhydrous Ethanol
Thermal energy consumed (MJ/tc) (a)	942.52	1012.18
Electric energy (MJ/tc) (b)	100.80	100.80
Total (MJ/tc) (a + b)	1043.32	1112.98
Surplus electrical energy—sent to the grid (MJ/tc) (c)	208.44	208.44
Steam losses (MJ/tc) (d)	47.13	50.61
Total (MJ/tc) (a + b + c + d)	1298.88	1372.03
Steam consumed in the process (kg steam/tc)	434.30	467.70

5.2.2. Losses in the Production Process—Industrial Stage

The loss in the ethanol production process refers to the loss of total reducing sugars (ART), which is 14.14%. However, in this study, the value 14.08% was considered for hydrated ethanol, this occurs due to the current sugarcane cleaning process in the industry using the dry cleaning process and not the sugarcane washing process, which promoted sucrose losses. For the production of anhydrous ethanol, the loss of ART is 15.56%. This increase in the loss of ART for the production of anhydrous ethanol occurs due to the dehydration process to obtain anhydrous ethanol [43].

The agricultural stage delivers an energy value for the industrial stage between 5011.83 MJ/tc to 4211.30 MJ/tc, according to the operational configurations of the production system adopted in this study, from this amount of energy received, the energy available in the juice extracted from the mills is 2125.72 MJ/tc, which is intended for ethanol production. The amount of anhydrous ethanol produced with the extracted juice is 80.4 L/tc, equivalent to 1794.96 MJ/tc, and the production system to produce anhydrous ethanol presents a loss of 330.76 MJ/tc. Therefore, 2125.72 MJ/tc of energy available in the juice is needed to produce anhydrous ethanol.

Similarly, to produce hydrated ethanol, 2125.72 MJ/tc of energy available in the juice is also required, that is, the amount of hydrated ethanol produced with the extracted juice is 85.47 L/tc, equivalent to 1826.31 MJ/tc, and the production system for hydrous ethanol production presents a loss of 299.42 MJ/tc [3].

5.2.3. Cogeneration System—Industrial Stage

The cogeneration process is responsible for meeting the demand for thermal energy and electricity through the burning of sugarcane bagasse in a boiler to be used in the ethanol production process, as well as the energy to be sold to an electricity distributor. The agricultural stage delivers an energy value for the industrial stage between 5011.83 MJ/tc to 4211.30 MJ/tc. The amount of energy needed for the production of ethanol is 2125.72 MJ/tc. Thus, the amount of bagasse of sugarcane available for cogeneration has an energy value between 2886.10 MJ/tc to 2085.58 MJ/tc. Of this amount of energy available for cogeneration, 1372.03 MJ/tc is converted into electricity and useful thermal energy for the production of anhydrous ethanol, meeting the demands for thermal energy and electricity. This difference in energy represents an amount of sugarcane bagasse to be used for future startups and/or eventual maintenance of the system.

Similarly, 1298.88 MJ/tc is converted into electricity and useful thermal energy to produce hydrous ethanol, meeting the demands for thermal energy and electricity. This energy difference represents an amount of sugarcane bagasse to be used for future departures and/or any system maintenance. Table 8 shows the amount of sugarcane bagasse used to generate energy for the production system and the amount of excess bagasse available for future departures and eventual system maintenance [3].

Table 8. Cogeneration system—Consumption of sugarcane bagasse.

Anhydrous Ethanol						
Available Energy	**Maximum**		**Average**		**Minimum**	
	Bagasse (kg/tc)	**Energy (MJ/tc)**	**Bagasse (kg/tc)**	**Energy (MJ/tc)**	**Bagasse (kg/tc)**	**Energy (MJ/tc)**
Thermal energy generated	77.17	1372.03	77.17	1372.03	77.17	1372.03
Thermal energy [1]	85.16	1514.08	62.64	1113.81	40.13	713.55
Total	162.32	2886.10	139.81	2485.84	117.30	2085.58
Hydrous Ethanol						
Available Energy	**Maximum**		**Average**		**Minimum**	
	Bagasse (kg/tc)	**Energy (MJ/tc)**	**Bagasse (kg/tc)**	**Energy (MJ/tc)**	**Bagasse (kg/tc)**	**Energy (MJ/tc)**
Thermal energy generated	73.05	1298.88	73.05	1298.88	73.05	1298.88
Thermal energy [1]	89.27	1587.22	66.76	1186.96	44.25	786.70
Total	162.32	2886.10	139.81	2485.84	117.30	2085.58

Sugarcane bagasse calorific value—dry and clean: 17.78 MJ/kg. [1] Thermal energy generated with excess bagasse (stops and occasional maintenance); sugarcane bagasse, dry basis.

5.2.4. Energy Consumption Level 2i—Industrial Stage

The energy consumption for the industrial stage, Level 2i, includes the energy embedded in the inputs used in the production of ethanol. During the industrial stage, this energy value was determined through the consumption of fossil energy in the production of industrial chemical inputs. This value is 0.23 MJ/L of ethanol produced [44]. Table 9 presents the main chemical products and lubricants used in industrial production processes, with average consumption values and associated energy [3].

Table 9. Embedded energy in the inputs used—Industrial sector—Level 2i.

Inputs	**Consumption (kJ/L Ethanol)**	**Energy Consumed (MJ/tc)**	
		Hydrous Ethanol	**Anhydrous Ethanol**
NaOH (Sodium Hydroxide)	98.60	8.43	7.93
Lime	64.90	5.55	5.22
Sulfuric acid	48.00	4.10	3.86
Cyclohexane	5.20	-	0.42
Defoamer	2.60	0.22	0.21
Lubricant	1.60	0.14	0.13
Others	2.00	0.17	0.16
Total	222.90	18.61	17.92

Hydrous ethanol production: 85.47 L/tc; Anhydrous ethanol production: 80.4 L/tc.

5.2.5. Energy Consumption Level 3i—Industrial Stage

The energy consumed for the construction of buildings is around 81.2 × 10^6 MJ, considering a constructed area of 10,800 m^2, with an energy consumption of 7.54 × 10^3 MJ/m^2, with a useful life of 50 years. For the construction and assembly of light and heavy equipment, the energy consumed is around 66.4 × 10^6 MJ and 43.2 × 10^6 MJ, respectively, with a useful life of 25 years for heavy equipment and 10 years for light equipment. The energy cost for maintenance of buildings and equipment is 4% p.a. regarding the energy consumed in construction [15]. In Table 10, energy consumption with infrastructure can be observed, that is, for buildings, light and heavy equipment that integrate industrial facilities in an autonomous distillery.

Table 10. Energy consumption with infrastructure—Industrial stage—Level 3i.

Infrastructure	Energy Consumed Building (MJ) × 10^6	Service Life (Years)	Energy Consumed Building (MJ/Years) × 10^6 (a)	Energy Consumed Maintaining (MJ/Years) × 10^6 (b)	Energy Consumed Total (MJ/Years) × 10^6 (a + b)	Energy Consumed (MJ/tc)
Edification	81.40	50	1.63	3.26	4.89	2.44
Heavy equipment	66.40	25	2.66	2.66	5.31	2.66
Light equipment	43.20	10	4.32	1.73	6.05	3.02
		Total			16.25	8.12

Milling capacity: 2,000,000 tc/ano; energy cost with maintenance, about the total energy consumed: 4% a.a.

5.2.6. Total Energy Consumption—Industrial Stage

The total energy consumption in the industrial stage corresponds to the sum of energy consumed in the activities of level 1i, level 2i, and level 3i. In this stage, the highest energy consumption is related to activities of level 1i, which is the production process itself. However, it should be noted that this energy is entirely provided by the cogeneration process, thermal, and electrical energy, and the excess electricity is sold with the local distributor; these results can be seen in Table 11.

Table 11. Total energy consumption in the industrial stage—Ethanol production.

	Industrial Stage	Hydrous Ethanol	Anhydrous Ethanol
Level 1i	Thermal energy consumed (MJ/tc)	942.52	1012.18
	Electricity (MJ/tc)	100.80	100.80
	Total (MJ/tc)	1043.32	1112.98
	Steam consumed in the process (kg vapor/tc)	434.30	467.70
Level 2i	Energy embedded in inputs used in ethanol production (MJ/tc)	18.61	17.92
Level 3i	Energy required for construction and maintenance of buildings and equipment used (MJ/tc)	8.12	8.12
	Total	1070.05	1139.02
Cogeneration	Steam loss in the process—5% (MJ/tc)	47.13	50.61
	Steam generated (kg vapor/tc)	456.02	491.09
	Thermal energy for the process (MJ/tc)	1043.32	1112.98
	Electricity sent to grid (MJ/tc)	208.44	208.44
	Thermal energy generated (MJ/tc)	1298.88	1372.03

Table 11. *Cont.*

	Industrial Stage	Hydrous Ethanol	Anhydrous Ethanol
Ethanol	Ethanol purity (%)	93.50	99.40
	Volume Produced (L/tc)	85.47	80.40
	Density (kg/L)	0.81	0.79
	Lower calorific value (MJ/kg)	26.38	28.26
	Energy (MJ/tc)	1826.31	1794.96

5.3. Energy Consumption in the Distribution Stage

The energy consumed in the distribution stage is presented as a function of the sum of energy consumption in three levels of regression: (a) Level 1d—Fossil energy consumed during the distribution process, which includes the transport of ethanol from the plants to the distributors and from the distributors to gas stations; (b) Level 2d—Energy embedded in inputs needed in the distribution process; and (c) Level 3d—Energy required for manufacturing and maintenance of transport equipment involved in transport.

5.3.1. Energy Consumption Level 1d—Distribution Stage

In this article, it is considered that the distribution of ethanol takes place in two stages. The first stage takes place between the producing plants and the distributors, and the second stage is between the distributors and the municipalities, that is, the end points of consumption.

The average distances for the state of São Paulo are 268.35 km between power plant and distribution and 68.93 km between distributors and end points of consumption. The average distances presented for the state of São Paulo will be considered as a reference for energy consumption, considering that this state is responsible for 46% of the country's ethanol production, according to data presented for the 2020/21 harvest published in August 2020 [45–47]. Another point that is considered in this study is that the transport of ethanol between plants and distributors takes place by means of Bitrem trucks, with a transport capacity of 45,000 L of ethanol and diesel consumption of 1.6 km/L. The Transport between distributors and consumption points is carried out using trucks, with a transport capacity of 15,000 L of ethanol and diesel consumption of 2.20 km/L. Table 12 presents the energy consumption for this level.

Table 12. Distribution stage consumption—Level 1d.

	Hydrous Ethanol	Anhydrous Ethanol
Distance		
Plant—Distributor (km)	268.35	268.35
Distributor—Point of Consumption (km)	68.93	-
Production (L/tc)	85.47	80.40
Transport vehicle—Load capacity		
Bit-train truck (L)	45,000.00	45,000.00
Truncated truck (L)	15,000.00	
Transport vehicle—Diesel Consumption		
Bi-train truck (km/L)	1.60	1.60
Truncated truck (km/L)	2.20	-
Energy consumption		
Plant—Distributor (MJ/tc)	11.22	10.55
Distributor—Point of Consumption (MJ/tc)	6.29	-
Total (MJ/tc)	17.50	10.55
Diesel Density (kg/L)	0.82	
Lower Calorific Power of Diesel (kJ/kg)	42,944.00	

5.3.2. Energy Consumption Level 2d—Distribution Stage

Much of the literature does not clearly and directly contemplate the inputs considered at this level, as described by the focus refers only to agricultural and industrial activities, about the energy evaluation of ethanol. The distribution activity, after the product leaves the mills until it reaches the consumer, is not commonly accounted for in energy costs. Despite the low representativeness, when comparing the distribution activity with the agricultural activity there is an energy expenditure that must be considered. Thus, for energy consumption for level 2d, energy expenditure with lubricants and tires is considered, for the lubricant input, the value is 0.71 MJ/tc, and for the tire input, the energy consumption is 0.628 MJ/km driven. The values found for hydrated ethanol and anhydrous ethanol, regarding the energy consumed referring to the tire input, presented values of 0.57 MJ/tc and 0.30 MJ/tc, respectively, as they are close values and of low magnitude. This study considers the value of energy consumption referring to the tire input of 0.57 MJ/tc; therefore, the energy consumption for level 2d is 1.28 MJ/tc, with 0.71 MJ/tc referring to the lubricant input and 0.57 MJ/tc for the tire input [46,47].

5.3.3. Energy Consumption Level 3d—Distribution Stage

The energy consumption for level 3d, for the distribution stage, is directly related to the manufacture and maintenance of the equipment used during the transport of ethanol from the plants to the distributors and from the distributors to the points of consumption. The results found for energy consumption are similar to those carried out to determine the energy consumption for maintenance and manufacturing of trucks used in the agricultural stage level 3a. However, with a change in the useful life from five years to seven years, due to its use, the total energy consumption for manufacturing and maintenance of trucks is 6563.00 MJ/ha, with an average production of 77.23 tc/ha and a useful life of seven years, which represents 12.48 MJ/tc [47].

5.3.4. Total Energy Consumption—Distribution Stage

The total energy consumption in the distribution stage corresponds to the sum of energy consumed in activities of level 1d, level 2d, and level 3d. In this stage, the highest energy consumptions are related to activities of level 1d, related to the transport of ethanol itself, and 3d level referring to the maintenance and manufacture of the equipment involved in this activity. Table 13 shows these consolidated results.

Table 13. Energy consumption in the distribution stage.

Regression Level	Hydrous Ethanol (MJ/tc)	Anhydrous Ethanol (MJ/tc)
Level 1d	17.50	10.55
Level 2d	1.28	1.28
Level 3d	12.14	12.14
Total	30.92	23.97

6. EROI in the Ethanol Production Flow

Energy return on investment (EROI) is the amount of energy that must be consumed to produce a certain amount of energy. So, when an EROI analysis is applied, consequently we are carrying out in the foreground an energy analysis of the production process to be analyzed [48,49].

A crucial step that is often neglected is the need to select the appropriate limits for an EROI analysis, and, based on these limits, it becomes possible to define the EROI due to the knowledge of the gross energy that the system delivers, as well as the amount of energy involved in the process for the production of this gross energy. So, the determination of the

EROI occurs through the relationship between the gross energy that the system delivers and the sum of the amount of energy for the production of this gross energy [50].

In the same way, the EROI can be interpreted as the ratio between the energy that the production system provides throughout its useful life and the energy needed to build, operate, and dismantle the entire production system; that is, to produce a gross flow energy constant, if a flow of energy is necessary to operate and maintain the project or enterprise, it must also be considered a construction energy consumption for the infrastructure involved and at the end of the project duration, some energy, for its deactivation, presenting in this way the total net energy production of the productive complex during its entire useful life [51].

In another way, the EROI can be defined as the ratio between the energy produced by the system and the energy invested in the system [52].

The EROI is presented as an indicator commonly used to report the general efficiency of the process. However, the arguments used are simplistic, mainly because this indicator does not consider whether the energy flow is of renewable or fossil origin [53]

However, some authors use the same formulation used for the EROI for the term energy balance. This occurs as a function of the ratio of the energy output and input portions, that is, the delivered energy portion in the numerator and the energy input portion in the denominator, or requested by the system [54].

In this way, the EROI can be described as an energy efficiency indicator based on the LCA (life cycle assessment) approach, in which it determines the amount of net energy produced by the source, taking into account the energy flows involved in all stages of the production process during its useful life for construction, fueling costs, maintenance, and decommissioning. To fulfill all the requirements of a bioeconomy, bioenergy production must also be analyzed in terms of energy efficiency. In this context, the EROI is generally used to show the advantages or disadvantages of a fuel or a biofuel, considering aspects such as the environment, energy balance, and even its economic aspects; that is, this indicator demonstrates the efficiency of the energy system through a simple relationship between the energy output and input of the system [55].

For the sugar and alcohol sector, the use of biomass as energy needs to consider the energy balance of the production chain for its production and subsequent transformation. The energy analysis of biomass, through the primary energy contained in sugarcane, can be an interesting alternative to the use of bagasse, straw, or sucrose independently. These types of studies are recommended to develop or update techniques that allow the primary energy of sugarcane to be used more efficiently [9]. For the sugarcane industry, some specialists in the sector have started to consider sugarcane as an energy raw material, rather than a food raw material, so other characteristics related to the total primary energy content have become important quality parameters. The second point deals with how efficient this primary energy is when converted into useful energy products such as ethanol and excess electricity [56].

In this article, based on the presented results of energy consumption in the ethanol production flow, the EROI will be determined through the relationship between the energy that the production system delivers to society and the energy consumption to produce this delivered energy. The energy that the system delivers to society refers to the energy contained in the volume of ethanol produced and the amount of excess electricity to be made available to the network, and the energy consumption of the system refers to the sum of the amount of energy consumed in each stage of the production process [3]. The values for the EROI in the ethanol production flow can be seen in Table 14.

In Appendix A of this article, the energy flow for the production of hydrated ethanol and anhydrous ethanol can be observed.

Table 14. EROI for the ethanol production flow.

Sugarcane		**Maximum**	**Minimum**	**Average**
Energy delivery by sugarcane		8071.18	6765.63	7418.41
Energy delivery by the system				
Hydrous ethanol (MJ/tc)	(A)		1826.31	
Anhydrous ethanol (MJ/tc)	(B)		1794.96	
Electricity sent to grid (MJ/tc)	(C)		208.44	
Energy consumed by the agricultural stage system		Maximum	Minimum	Average
Level 1a (MJ/tc)		114.71	101.42	108.07
Level 2a (MJ/tc)		113.43	95.69	104.56
Level 3a (MJ/tc)		29.98	24.40	26.69
Total (MJ/tc)	(D)	257.12	221.21	239.16
Energy consumed by the industrial stage system		Hydrous ethanol	Anhydrous ethanol	
Level 1i (MJ/tc)	(E1)	1043.32	1112.98	
Level 2i (MJ/tc)		18.61	17.92	
Level 3i (MJ/tc)		8.12	8.12	
Total (MJ/tc)	(E)	1070.05	1139.02	
Energy consumed by the distribution stage system		Hydrous ethanol	Anhydrous ethanol	
Level 1d (MJ/tc)		17.50	10.55	
Level 2d (MJ/tc)		1.28	1.28	
Level 3d (MJ/tc)		12.14	12.14	
Total (MJ/tc)	(F)	30.92	23.97	
EROI for Ethanol Production Flow				
Industrial stage		**Maximum**	**Minimum**	**Average**
Hydrous ethanol	(3)	1.58	1.53	1.55
Anhydrous ethanol	(4)	1.47	1.43	1.45
Distribution Stage		**Maximum**	**Minimum**	**Average**
Hydrous ethanol	(5)	1.54	1.50	1.52
Anhydrous ethanol	(6)	1.45	1.41	1.43
EROI for Ethanol Production Flow—Using Only Fossil Fuel				
Industrial Stage		**Maximum**	**Minimum**	**Average**
Hydrous ethanol	(7)	8.20	7.17	7.65
Anhydrous ethanol	(8)	8.09	7.08	7.55
Distribution Stage		**Maximum**	**Minimum**	**Average**
Hydrous ethanol	(9)	7.29	6.46	6.85
Anhydrous ethanol	(10)	7.38	6.52	6.92

EROI calculation: (3) (A + C)/(D + E); (4) (B + C)/(D + E); (5) (A + C)/(D + E + F); (6) (B + C)/(D + E + F); (7) (A + C)/[D + (E − E1)]; (8) (B + C)/[D + (E − E1)]; (9) (A + C)/[D + (E − E1) + F]; (10) (B + C)/[D + (E − E1) + F].

7. Competitiveness of Sugarcane Ethanol Compared to Fossil Fuels

The competitiveness of sugarcane ethanol produced in Brazil with fossil fuels, specifically gasoline, can be evaluated through two factors: (a) environmental benefits; and (b) energy efficiency in the sugarcane ethanol production process compared to gasoline.

The factor-related to environmental benefits in the use of sugarcane ethanol is justified by the reduction in greenhouse gas emissions. This reduction is due to a lower volume of carbon dioxide emissions from cultivation to combustion compared to fossil fuels. Another environmental benefit of using sugarcane ethanol is the use of sugarcane as a raw material, a source of renewable energy, and the generation of residual energy through the use of residues such as bagasse and vinasse for additional energy generation, contributing to the overall energy efficiency of the process [3].

On the other hand, ethanol produced in Brazil has about 34% less energy per unit volume than gasoline. However, the cost–benefit of ethanol compared to gasoline is not solely based on the amount of available energy, considering that ethanol has a higher octane rating, which enhances performance beyond the expected 66% of gasoline, corresponding to the difference in pure energy content [57].

To assess the factors related to energy efficiency, it is important to understand the characteristics of gasoline produced and marketed in Brazil. Gasoline in Brazil consists of molecules with 5 to 12 carbons and is called type A gasoline. It has a higher heating value of 47 MJ/kg and a density of 0.745 g/cm^3. To be sold in Brazil, distributors must blend type A gasoline with anhydrous ethanol, and this blend becomes known as type C gasoline.

The percentage of anhydrous ethanol in the blend can vary between 18 and 27%, as determined by the Interministerial Council of Sugar and Alcohol (CIMA) [58].

The production of sugarcane ethanol in Brazil is limited by the need for space for cultivation and competition with other food crops. In Brazil, ethanol is more expensive than gasoline; however, this biofuel is responsible for fueling flex-fuel vehicles. In 2019, Brazil produced 35.307 million liters of ethanol, of which 24.899 million liters were hydrated and 10.407 million liters were anhydrous. The hydrated form is used directly in vehicles with engines that allow its use, and the anhydrous form is blended with gasoline [59].

The energy efficiency of the production process of a fuel can be verified and compared through the Energy Return on Investment (EROI). In this context, the EROI of gasoline produced and marketed in Brazil varies between 2.34 and 5.53 for type A gasoline and between 3.12 and 5.50 for type C gasoline, according to data presented for the period from 2010 to 2019 [58].

Therefore, factors related to environmental benefits, energy generation through residues, and energy efficiency in the production process of ethanol, when compared to gasoline, are more advantageous, justifying the competitiveness of ethanol against gasoline.

8. Conclusions

The results presented for the EROI (Energy Return on Investment) of sugarcane ethanol are satisfactory and robust, confirming the current production format used in sugarcane ethanol plants. When evaluating the values for the EROI of ethanol in both the industrial and distribution stages, they are above 1.00. This indicates a return on invested energy, although these values are low due to the high energy consumption in the agricultural and industrial stages.

However, when calculating the EROI of ethanol using only the fossil fuel utilized, considering the autonomy in energy generation in sugarcane ethanol plants, the values found for the EROI of ethanol in the industrial stage range between 8.20 and 7.08. For the distribution stage, these values are between 7.29 and 6.52, demonstrating a significant increase and strongly validating the return on invested energy and the current production model in an autonomous ethanol production plant.

On the other hand, the EROI for gasoline produced and sold in Brazil ranges between 2.34 and 5.53 for type A gasoline and between 3.12 and 5.50 for type C gasoline. Therefore, the comparison between the values presented for the EROI of sugarcane ethanol and the EROI of gasoline demonstrates the complete competitiveness of sugarcane ethanol compared to gasoline, particularly considering environmental factors and energy efficiency in the production flow.

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Appendix A

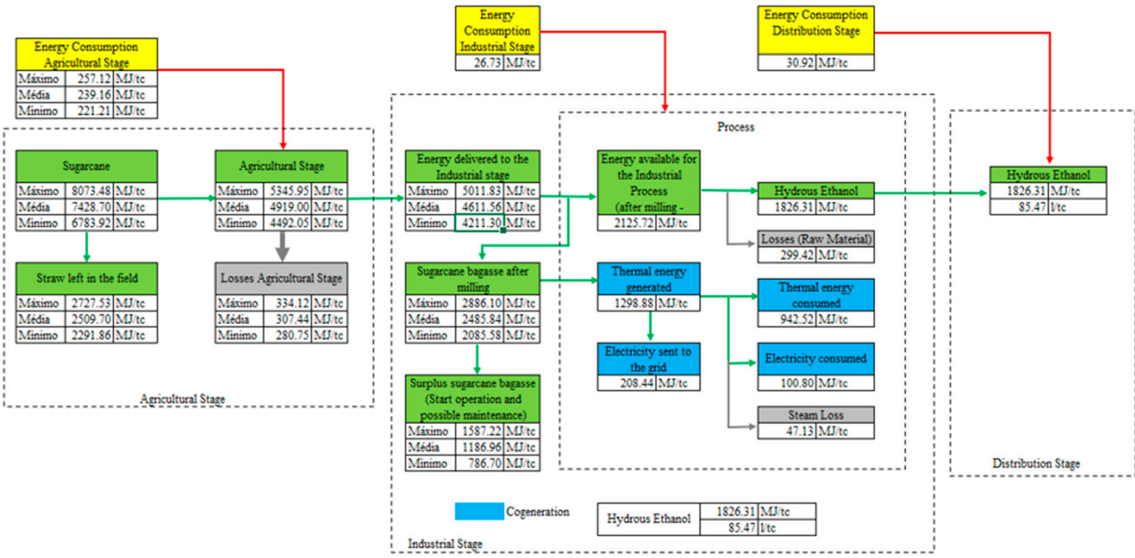

Figure A1. Energy flow–hydrous ethanol.

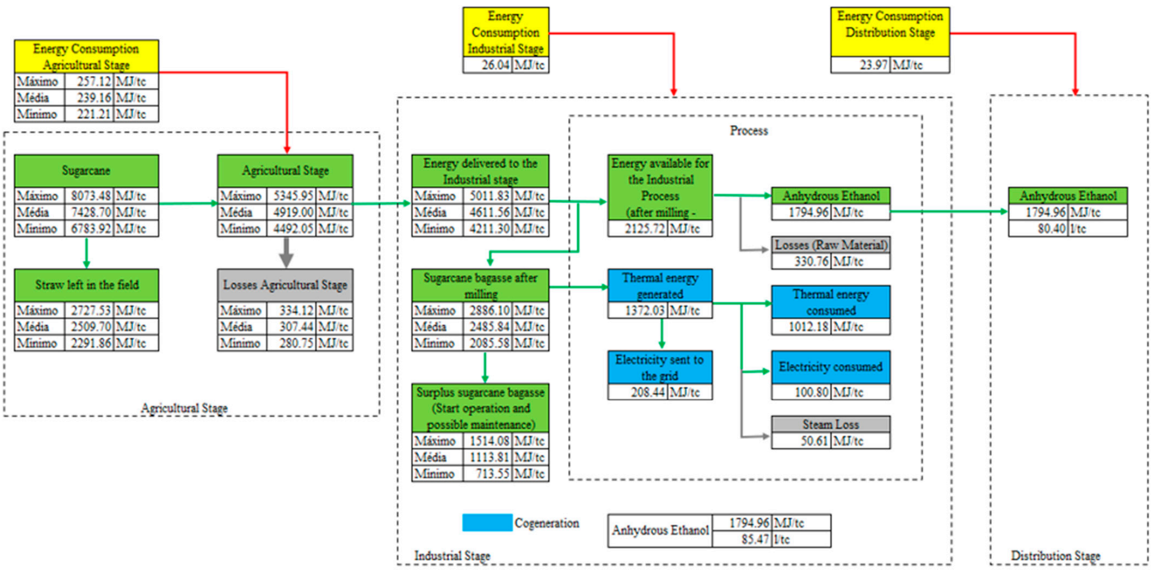

Figure A2. Energy flow–anhydrous ethanol.

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