Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Thermodynamic and Thermoeconomic Assessment of a Sugarcane–Corn Flex Biorefinery

Glauber Rocha

glauber.rocha@ifms.edu.br

Federal Institute of Mato Grosso do Sul (IFMS)

C. E Tuna

São Paulo State University

Research Article

Keywords: Biomass conversion, Flex biorefinery, Exergy analysis, Thermoeconomic analysis, Cogeneration, Sugarcane–corn integration, Bioethanol.

Posted Date: June 16th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9428121/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Thermodynamic and Thermoeconomic Assessment of a Sugarcane–Corn Flex Biorefinery

Rocha, G. [1,2]*; Tuna, C.E[1].

[1] Laboratory of Optimization of Energy Systems (LOSE), Department of Chemistry and Energy, School of Engineering, and Institute of Bioenergy Research (IPBEN-UNESP) – Associated Laboratory of Guaratinguetá, São Paulo State University (UNESP), Guaratinguetá, SP, Brazil.

[2] Federal Institute of Mato Grosso do Sul (IFMS), Campus Ponta Porã, MS, Brazil.

*Corresponding author:

Glauber Rocha (glauber.rocha@ifms.edu.br).

Co-authors: celso.tuna@unesp.br

Abstract

Flexible sugarcane–corn biorefineries have emerged as a promising strategy to enhance biomass conversion efficiency and ensure year-round operation in Brazil's bioenergy sector. However, the thermoeconomic behavior of such systems remains insufficiently explored. This study presents a comprehensive exergoeconomic assessment of a sugarcane–corn flex biorefinery operating under three scenarios: (1) seasonal sugarcane-only production, (2) off-season corn ethanol production using stored bagasse, and (3) fully integrated year-round operation. The methodology combines mass, energy, and exergy balances with exergy-based cost accounting to quantify the monetary impact of exergy destruction and identify the main thermoeconomic cost drivers. Results demonstrate that full integration significantly enhances system performance, increasing overall annual efficiency from 25.27% to 61.26% through improved steam management, reduced irreversibilities, and minimized unused thermal resources. These improvements are directly reflected in economic performance, with the production costs of sugarcane ethanol and surplus electricity estimated at 1.42 BRL L^{-1} and 60.31 BRL MWh^{-1}, respectively. Sensitivity analysis further indicates that the integrated configuration maintains superior economic performance across a wide range of feedstock prices and electricity market conditions, demonstrating its operational robustness. Overall, this study advances the understanding of thermoeconomic behavior in flexible biorefineries by explicitly linking exergy destruction to cost formation and provides a consistent framework to support decision-making toward more efficient and economically resilient bioenergy systems.

Keywords

Biomass conversion; Flex biorefinery; Exergy analysis; Thermoeconomic analysis; Cogeneration; Sugarcane–corn integration; Bioethanol.

1. Introduction

1.1. Background and Motivation

The global transition toward sustainable energy systems, driven by the urgent need to mitigate climate change, has intensified the deployment of biomass conversion technologies. In this context, biorefineries have emerged as key platforms for the sustainable production of biofuels, bioelectricity, and value-added bioproducts, contributing to the development of low-carbon and circular bioeconomy systems. Among these, steam-based cogeneration systems integrated into biomass-fired biorefineries provide an efficient pathway for the simultaneous generation of fuels, electricity, and thermal energy. Beyond their role in the bioenergy sector, such systems constitute complex thermal energy networks whose optimization is essential for enhancing overall energy efficiency and resource utilization.

Brazil represents a strategic case study due to its vast availability of agricultural biomass and its well-established ethanol industry. According to recent estimates for the 2024/2025 harvest, Brazilian ethanol production reached 36.1 billion liters, with corn-based ethanol accounting for approximately 7.2 billion liters [1]. This expansion has stimulated the development of flexible biorefineries that integrate sugarcane and corn feedstocks, enabling continuous or year-round operation while maximizing the utilization of existing agro-industrial infrastructure and cogeneration assets [2,3]. In this study, the term "flex biorefinery" refers to an integrated facility capable of processing both sugarcane and corn, thereby enhancing operational flexibility and asset utilization.

Previous studies have investigated the thermodynamic performance of sugarcane-based plants and the benefits of integrating additional feedstocks. Dias et al. [2], for example, demonstrated that autonomous and flexible configurations can enhance energy efficiency through process diversification and improved cogeneration. Nevertheless, despite the growing body of literature on thermodynamic and exergoeconomic analyses of biomass-based systems, most investigations remain limited to seasonal or single-feedstock operations. Consequently, the thermodynamic implications of operational flexibility—particularly those associated with steam network reconfiguration and year-round cogeneration—have not been sufficiently explored.

Recent research on sugarcane–corn flexible biorefineries has primarily focused on environmental assessments or process integration aspects [4], with comparatively limited attention to the distribution of exergy flows, the characterization of irreversibilities, and their direct relationship with cost formation. In particular, the integration of corn processing during the off-season introduces new thermodynamic interactions within the steam and power generation systems that are not adequately captured in existing models.

Therefore, there remains a clear need for a comprehensive framework capable of evaluating how the transition from seasonal to continuous operation influences the thermodynamic behavior of steam-based cogeneration systems. To address this gap, the present study develops a detailed thermodynamic and exergoeconomic assessment of a flexible sugarcane–corn biorefinery operating under three distinct configurations, with emphasis on quantifying how operational flexibility affects energy efficiency, exergy destruction, and the formation of production costs.

Although the case study is based on Brazilian operating conditions, the methodological framework proposed in this work is broadly applicable to biomass-fired cogeneration systems worldwide. As such, the findings provide generalized design insights that support the optimization of integrated thermal energy systems in diverse biomass-rich regions.

1.2. Thermoeconomic Framework and Literature Context

Thermoeconomic, also referred to as exergoeconomic, analysis provides a rigorous framework for integrating thermodynamic principles with economic evaluation in complex biomass conversion systems. By combining the Second Law of Thermodynamics with cost accounting methodologies, this approach assigns monetary values to exergy flows and irreversibilities, enabling the identification of inefficiencies and the realistic estimation of production costs associated with energy and material streams. Consequently, exergoeconomic analysis has become a valuable tool for the design, optimization, and performance assessment of steam-based cogeneration systems and integrated biorefineries [5–8].

A substantial body of literature has applied exergy and exergoeconomic methodologies to biomass-based energy systems. Junqueira et al. [9] demonstrated that the integration of first- and second-generation ethanol pathways can significantly reduce overall production costs through improved exergy utilization. Similarly, Pellegrini and Oliveira Jr. [8] showed that exergoeconomic analysis is particularly effective for comparing the technical and economic performance of advanced cogeneration configurations in sugarcane-based plants. These studies underscore the capability of exergy-based costing to reveal key cost drivers and to support strategic decision-making in complex bioenergy and biomass conversion systems.

Despite these advances, most existing investigations are limited to autonomous plants or steady-state evaluations during the harvest period. As a result, the thermoeconomic implications of operational variability and multi-feedstock integration—particularly in flexible sugarcane–corn biorefineries—remain insufficiently explored. The influence of varying operating conditions on exergy destruction patterns, steam network interactions, and cost formation in integrated thermal systems has received comparatively little attention in the literature.

Therefore, a clear need exists for comprehensive analyses that extend exergoeconomic evaluation to flexible and dynamically operated biomass-based cogeneration systems. Addressing this gap is essential for improving the understanding of how thermodynamic inefficiencies propagate through integrated thermal networks and influence the economic performance of such systems. The present study contributes to this objective by providing a detailed thermodynamic and exergoeconomic assessment of a flexible sugarcane–corn biorefinery operating under distinct seasonal and year-round configurations.

1.3. Cogeneration and Energy Optimization in Flex Plants

In biomass-fired biorefineries, cogeneration systems play a pivotal role in enhancing overall thermal efficiency and ensuring energy self-sufficiency. The use of sugarcane bagasse as the primary fuel enables the simultaneous production of process steam and electricity, thereby improving fuel utilization and reducing dependence on external energy sources [3]. From a thermal engineering perspective, the integration of cogeneration with multiple biomass conversion routes creates complex interactions within the steam and power generation network, requiring careful management to minimize irreversibilities and optimize system performance.

Flexible biorefinery configurations, commonly referred to as Flex 360, extend these benefits by enabling continuous operation during both harvest and off-season periods. In this study, the term “Flex 360” denotes an integrated facility capable of

processing sugarcane during the harvest season and corn throughout the year, thereby maximizing the utilization of installed cogeneration capacity and enhancing the stability of the thermal energy supply. This operational strategy increases asset utilization, improves energy efficiency, and contributes to the economic resilience of the biorefinery.

However, the transition from seasonal to year-round operation introduces additional technical and operational challenges. In particular, the strategic management of sugarcane bagasse stocks becomes essential to meet the higher thermal demand associated with corn processing during the off-season. Efficient biomass storage and optimized steam distribution are therefore critical to maintaining stable and efficient system performance [10,12]. These aspects highlight the importance of integrated thermodynamic and economic assessments to support decision-making in flexible biorefinery design and operation.

To isolate the thermodynamic and economic interactions between the integrated feedstocks, the present study considers a standalone ethanol distillery configuration as a system boundary, excluding the sugar production route. This assumption enables a clearer evaluation of the energy trade-offs and cost formation mechanisms associated with the transition toward a fully integrated sugarcane–corn system, while maintaining focus on the performance of the steam-based cogeneration network.

Building upon previous thermodynamic investigations of integrated ethanol production [2], the analysis examines three representative operational configurations: (i) seasonal sugarcane processing during the harvest period; (ii) the incorporation of a corn ethanol pathway during the off-season; and (iii) continuous year-round operation integrating both feedstocks within a Flex 360 framework. This comparative approach allows for a systematic assessment of how operational flexibility influences steam utilization, exergy destruction patterns, and the overall thermodynamic and economic efficiency of the cogeneration system.

1.4. Scientific Contributions and Research Objectives

The principal scientific contribution of this work is the integrated thermodynamic and exergoeconomic assessment of a steam-based cogeneration system embedded within a flexible sugarcane–corn biorefinery operating under both seasonal and year-round configurations. By addressing the interaction between biomass conversion pathways and energy generation systems, the study provides a comprehensive evaluation of how operational flexibility influences exergy flows, the distribution of irreversibilities, and the formation of production costs within integrated thermal energy systems.

Unlike conventional analyses that focus on single-feedstock plants or steady-state operation, the proposed approach systematically quantifies the relationship between thermodynamic inefficiencies and economic performance. By explicitly linking exergy destruction to cost formation, the study offers detailed insights into how different operational strategies affect the efficiency and economic viability of biomass-fired cogeneration systems. This contribution advances the state of the art by elucidating the thermoeconomic implications of transitioning from seasonal to continuous operation in flexible biorefineries and by providing transferable design and operational insights applicable to biomass-based energy systems worldwide.

To achieve these contributions, the specific objectives of this study are to:

1) Calculate the specific exergy cost (c_e) of the main energy streams and final products, establishing a direct relationship between thermodynamic performance and cost formation;

2) Determine the total exergoeconomic production costs for three distinct operational scenarios representing seasonal and year-round operation;

3) Identify the subsystems with the highest exergy destruction rates and quantify their contributions to the costs of final products and internal utilities;

4) Compare the thermodynamic and economic performance of the evaluated configurations to determine the most efficient and economically viable strategy for continuous operation; and

5) Perform a sensitivity analysis to assess how variations in key economic parameters, such as feedstock prices and electricity market values, influence cost formation and the economic competitiveness of the system.

2. Process Description and Modeling

2.1. Operational Strategies in Sugarcane–Corn Flex Biorefineries

Corn ethanol production in Brazil has been consolidated through different plant configurations: those dedicated exclusively to corn processing and the so-called *flex* plants, which are integrated with sugarcane mills [10]. The latter stand out for their ability

to utilize existing infrastructure for corn processing, operating either during the sugarcane off-season or continuously throughout the year, as in the *Flex 360* model [11]. Figure 1 schematically illustrates these three main configurations—Full Corn, Flex, and Flex 360—highlighting their operational and energetic strategies.

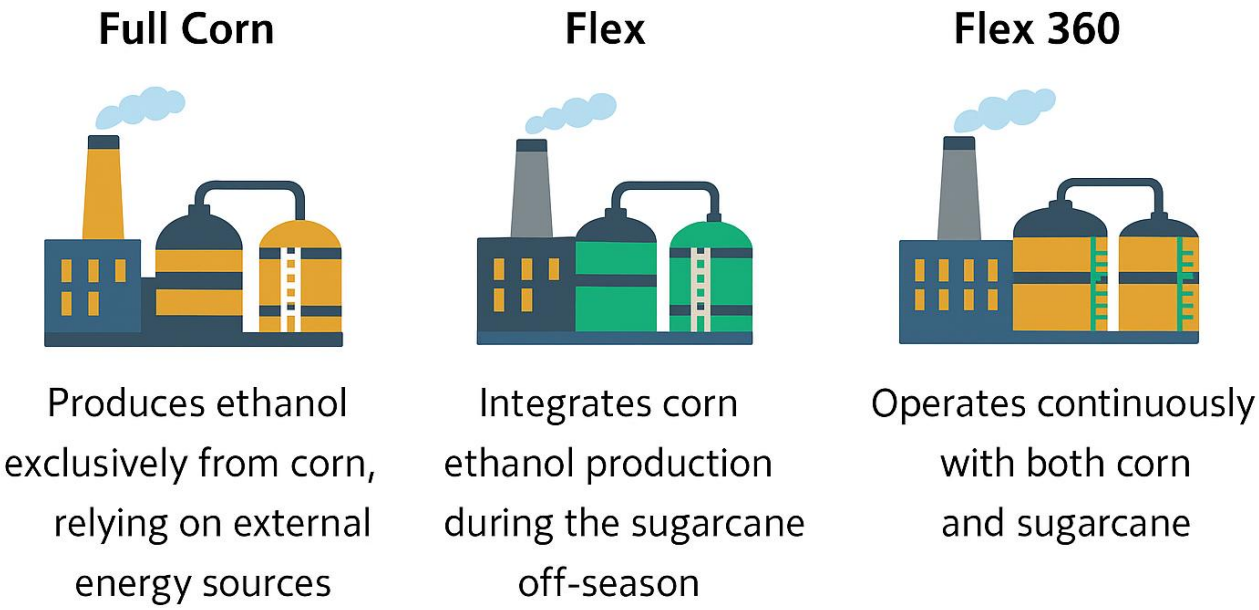


Figure 1. Corn Ethanol Plant Models in Brazil [11].

The integration of sugarcane- and corn-based ethanol production processes can occur at two main levels: energetic and structural [12]. At the energetic level, sugarcane bagasse, which possesses a high calorific value, can supply the thermal energy required for corn processing. This synergy allows the corn plant to achieve energy self-sufficiency, reducing dependence on external fuels such as natural gas or wood chips and resulting in lower operational costs [13]. At the structural level, the two production routes share equipment and systems such as boilers, distillation columns, fermenters, deaerators, and utility networks. This integration increases the utilization rate of industrial assets and dilutes fixed investments, enhancing the economic resilience and competitiveness of the facility [3,10].

Figure 2 illustrates a simplified representation of the integration between sugarcane- and corn-based ethanol processes in a flex configuration, highlighting the use of existing infrastructure from the sugarcane mill to support corn processing [10]. Depending on the technologies adopted—such as milling, hydrolysis, fermentation, and utility systems—the layout and degree of integration may vary across facilities. These operational arrangements provide the basis for defining the process assumptions, integration points, and thermoeconomic boundaries adopted in this study.

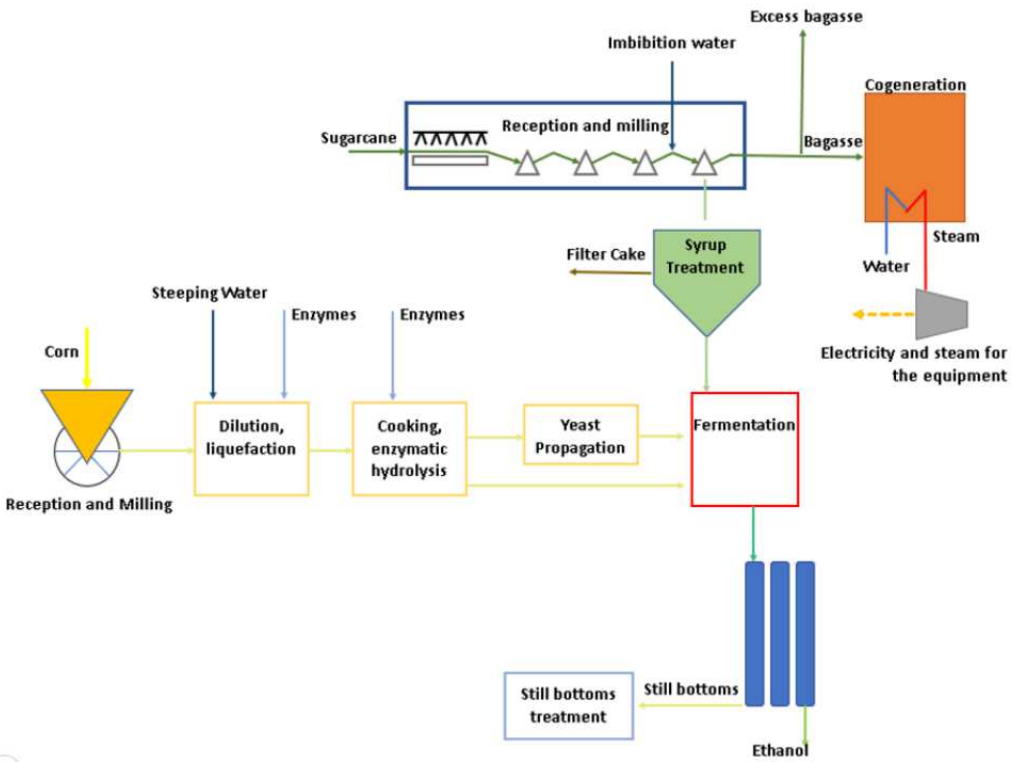


Figure 2 Illustrative Scheme of a Flex Plant or Integrated Plant. Source: Adapted from [10].

2.2. Process Configuration and General Assumptions

The integration of sugarcane and corn ethanol production routes introduces both technical and operational challenges related to energy balance and the combined operation of subsystems. Corn processing requires a considerably higher thermal load, particularly during the cooking and distillation stages, which demands efficient management of bagasse stocks during the sugarcane off-season [10,12]. From a structural standpoint, adaptations include adjustments to boilers, turbines, biomass feeding systems, and distillation units. Flex plants operating year-round minimize idle periods, improve global thermal efficiency, and extend the utilization of the installed cogeneration capacity [13]. The ability to operate in hybrid mode maximizes resource use and maintains high productivity even outside the harvest period.

Beyond ethanol production, process integration enhances the generation of high-value coproducts such as corn oil and DDGS (dried distillers grains with solubles) [11]. These additional product streams diversify revenue sources and mitigate market risks associated with ethanol price fluctuations. However, economic assessment based solely on market prices may overlook the impact of thermodynamic inefficiencies on production costs. Therefore, it is crucial to incorporate exergoeconomic costing, which attributes a monetary value to exergy destruction and inefficiencies throughout the process [12,14]. This approach enables a comprehensive understanding of the cost formation of both products and coproducts, providing strategic insights into process optimization, product allocation, and investment decisions.

Based on these operational and thermoeconomic premises, the following section details the specific configurations and input data adopted for each analyzed scenario.

2.3. Operational Scenarios and Data

This study evaluates three operational scenarios—Case 1, Case 2, and Case 3—representing different stages of technological integration and operational flexibility in a Brazilian ethanol complex.

Case 1 describes the initial configuration of a sugarcane-based ethanol plant designed for self-sufficient energy generation. The system includes a high-pressure boiler, a backpressure turbine, and a diffuser capable of processing up to 17,000 tons of cane per day (TCD). The primary objective of this configuration is to meet internal thermal and electrical demands without energy export.

Case 2 represents an expansion stage in which corn ethanol production is incorporated during the off-season, while maintaining sugarcane processing during the harvest period. In this configuration, the cogeneration system is optimized to supply both processes, enabling partial energy export and the simultaneous production of ethanol, corn oil, and DDGS.

Case 3 corresponds to the *Flex 360* concept, where the plant operates continuously throughout the year by integrating sugarcane and corn ethanol production. This configuration aims to fully utilize the available cogeneration capacity, increase annual productivity, and reduce operational downtime between harvest and off-season periods.

Table 1 presents the general operating data for the studied cases, including main flow rates, steam parameters, and process conditions.

Table 1 General data of the configuration of the studied cases.

		Harvest			Off-season		
Parameters	**Unit**	**Case 1**	**Case 2**	**Case 3**	**Case 1**	**Case 2**	**Case 3**
Input	-	Sugarcane	Sugarcane	Sugarcane	Corn	Corn	Corn
Operating Days	[days]	225	225	225	—	95	320
Daily Milling	[t/day]	8000	8000	8000	—	5536	5536
Bagasse-to-Steam Ratio	—	0.44	0.44	0.44	0.44	0.44	0.44
Total Bagasse Production	[t/h]	83.16	83.16	83.16	—	—	—
Surplus Bagasse	[t/h]	13.16	13.16	13.16	—	—	—

Note: In Case 3 (Flex 360), the value of 320 operating days refers to the total annual corn processing period, which includes simultaneous operation with sugarcane during the harvest season (225 days) and an additional 95 days during the off-season. Therefore, the total annual plant operation is approximately 320 days.

The following paragraphs describe each configuration in more detail.

Case 1 – Conventional Sugarcane Ethanol Plant

This configuration represents the baseline condition of a self-sufficient sugarcane-based ethanol plant. It includes a high-pressure boiler (43 bar, 400 °C), a backpressure turbine (25 MW nominal power), and a diffuser capable of processing up to 17,000 tons of cane per day (TCD). The plant's main objective is to meet its internal electrical and thermal demands without exporting surplus power to the grid.

Case 2 – Off-Season Corn Integration

Case 2 corresponds to the integration of corn ethanol production during the sugarcane off-season while maintaining sugarcane processing during harvest periods. The cogeneration system is optimized to supply both production routes, ensuring the generation of electricity and steam for the distilleries. This configuration allows partial electricity export and introduces coproducts such as corn oil and DDGS, improving economic diversification.

Case 3 – Flex 360 Continuous Operation

Case 3 represents the *Flex 360* concept, where sugarcane and corn ethanol production occur simultaneously throughout the year. This fully integrated configuration maximizes equipment utilization, increases annual ethanol output, and minimizes idle periods between harvests. Continuous operation allows a balanced energy demand profile, optimizing the use of bagasse as the primary fuel for cogeneration.

Table 2 summarizes the key thermodynamic parameters of the three scenarios, and Table 3 details the main mass and energy flow rates derived from the simulation results.

Table 2. Harvest Season Operational Parameters.

Points	Case 1					Case 2					Case 3				
	$\dot{m}[\frac{t}{h}]$	$T[^{o}C]$	$P[bar]$	$h[\frac{kj}{kg}]$	$s[\frac{kj}{kg.K}]$	$\dot{m}[\frac{t}{h}]$	$T[^{o}C]$	$P[bar]$	$h[\frac{kj}{kg}]$	$s[\frac{kj}{kg.K}]$	$\dot{m}[\frac{t}{h}]$	$T[^{o}C]$	$P[bar]$	$h[\frac{kj}{kg}]$	$s[\frac{kj}{kg.K}]$
1	159	440	43	3303.5	6.9	159	440	43	3303.5	6.9	159	440	43	3303.5	6.9
2	28.44	440	43	3303.5	6.9	157.6	440	43	3303.5	6.9	157.6	440	43	3303.5	6.9
3	28.44	127.4	2.5	2708.8	7	157.6	127.4	2.5	2708.8	7	157.6	127.4	2.5	2708.8	7
4	130.6	440	43	3303.5	6.9	1.4	440	43	3303.5	6.9	1.4	440	43	3303.5	6.9
5	130.6	413.1	2.5	3303.5	8.2	1.4	413.1	2.5	3303.5	8.2	1.4	413.1	2.5	3305.5	8.2
6	159	361.7	2.5	3209.2	8	159	367.6	2.5	3209.2	8	159	127.4	2.5	3209.2	8
7	161	345.5	2.5	3175.6	7.9	161	351.3	2.5	3175.6	7.9	171	127.4	2.5	3019.4	7.7
8	64.9	345.5	2.5	3175.6	7.9	64.9	351.3	2.5	3175.6	7.9	9.1	127.4	2.5	3019.4	7.7
9	96.1	345.5	2.5	3175.6	7.9	96	351.3	2.5	3175.6	7.9	161.9	127.4	2.5	3019.4	7.7
10	83.3	351.3	2.5	3175.6	7.9	83.3	351.3	2.5	3175.6	7.9	153.6	127.4	2.5	3019.4	7.7
11	—	—	—	—	—	—	—	—	—	—	67.2	127.4	2.5	3019.4	7.7
12	—	—	—	—	—	—	—	—	—	—	67.2	107.4	2.5	450.5	1.4
13	83.3	351.3	2.5	3175.6	7.9	83.3	351.3	2.5	3175.6	7.9	86.4	127.4	2.5	3019.4	7.7
14	83.3	107.4	2.5	450.5	1.4	83.3	107.4	2.5	450.5	1.4	86.4	107.4	2.5	450.5	1.4
15	86.4	107.4	2.5	450.5	1.4	86.4	107.4	2.5	450.5	1.4	153.6	107.4	2.5	450.5	1.4
16	12.7	351.3	2.5	3175.6	7.9	12.7	351.3	2.5	3175.6	7.9	6.9	274.6	2.5	3019.4	7.7
17	64.9	30	2.5	125.9	0.4	64.9	30	2.5	125.9	0.4	10.4	30	2.5	125.9	0.4
18	161	120	2.5	503.8	1.5	161	120	2.5	503.8	1.5	171	120	2.5	503.8	1.5
19	2	120	2.5	503.8	1.5	2	120	2.5	503.8	1.5	12	120	2.5	503.8	1.5
20	159	120	2.5	503.8	1.5	159	120	2.5	503.8	1.5	159	120	2.5	503.8	1.5
21	159	120	43	508.6	1.5	159	120	43	508.6	1.5	159	120	43	508.6	1.5

Table 3. Off-Season Operational Parameters.

Points	Case 1					Case 2					Case 3				
	$\dot{m}[\frac{t}{h}]$	$T[^{o}C]$	$P[bar]$	$h[\frac{kj}{kg}]$	$s[\frac{kj}{kg.K}]$	$\dot{m}[\frac{t}{h}]$	$T[^{o}C]$	$P[bar]$	$h[\frac{kj}{kg}]$	$s[\frac{kj}{kg.K}]$	$\dot{m}[\frac{t}{h}]$	$T[^{o}C]$	$P[bar]$	$h[\frac{kj}{kg}]$	$s[\frac{kj}{kg.K}]$
1	—	—	—	—	—	69.2	440	43	3303.5	6.9	69.2	440	43	3303.5	6.9
2	—	—	—	—	—	69.2	440	43	3303.5	6.9	69.2	440	43	3303.5	6.9
3	—	—	—	—	—	69.2	127.4	2.5	2708.8	7	69.2	127.4	2.5	2708.8	7
4	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
5	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
6	—	—	—	—	—	69.2	307.9	2.5	3086.9	7.8	69.2	307.9	2.5	3086.9	7.8
7	—	—	—	—	—	82	127.4	2.5	2683.6	6.9	82	127.4	2.5	2683.6	6.9
8	—	—	—	—	—	10.2	127.4	2.5	2683.6	6.9	10.2	127.4	2.5	2683.6	6.9
9	—	—	—	—	—	71.8	127.4	2.5	2683.6	6.9	71.8	127.4	2.5	2683.6	6.9
10	—	—	—	—	—	67.2	127.4	2.5	2683.6	6.9	67.2	127.4	2.5	2683.6	6.9
11	—	—	—	—	—	67.2	127.4	2.5	2683.6	6.9	67.2	127.4	2.5	2683.6	6.9
12	—	—	—	—	—	67.2	107.4	2.5	450.5	1.4	67.2	107.4	2.5	450.5	1.4
13	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
14	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
15	—	—	—	—	—	67.2	107.4	2.5	450.5	1.4	67.2	107.4	2.5	450.5	1.4
16	—	—	—	—	—	4.6	127.4	2.5	2683.6	6.9	4.6	127.4	2.5	2683.6	6.9
17	—	—	—	—	—	10.2	30	2.5	125.9	0.4	10.2	30	2.5	125.9	0.4
18	—	—	—	—	—	82	120	2.5	503.8	1.5	82	120	2.5	503.8	1.5
19	—	—	—	—	—	12.8	120	2.5	503.8	1.5	12.8	120	2.5	503.8	1.5
20	—	—	—	—	—	69.2	120	2.5	503.8	1.5	69.2	120	2.5	503.8	1.5
21	—	—	—	—	—	69.2	120	43	508.6	1.5	69.2	120	43	508.6	1.5

A schematic representation of the thermal power plant corresponding to Cases 1–3 is shown in Figure 3. In this diagram, an expansion valve located between points 4 and 5 allows the diversion of generated steam before it reaches the turbogenerator (between points 2 and 3), thereby enabling the adjustment of operating pressure according to system demands. Point 8 exclusively represents the steam that is not utilized by any process unit in the ethanol or coproduct sections; it is therefore surplus steam with no productive application.

The inlet of treated water to the deaerator at point 17 is determined by the system's mass balance to compensate for the steam discharged at point 8. Meanwhile, steam is supplied to the flex distillery at point 10, with sugarcane processed between points 13 and 14 and corn between points 11 and 12. The feedwater pump and the boiler are located between points 20 and 1, completing the steam generation circuit.

The thermodynamic and operational parameters of the analyzed configurations are summarized in Tables 2 and 3. The schematic representation of the thermal power plant corresponding to these scenarios is shown in Figure 3.

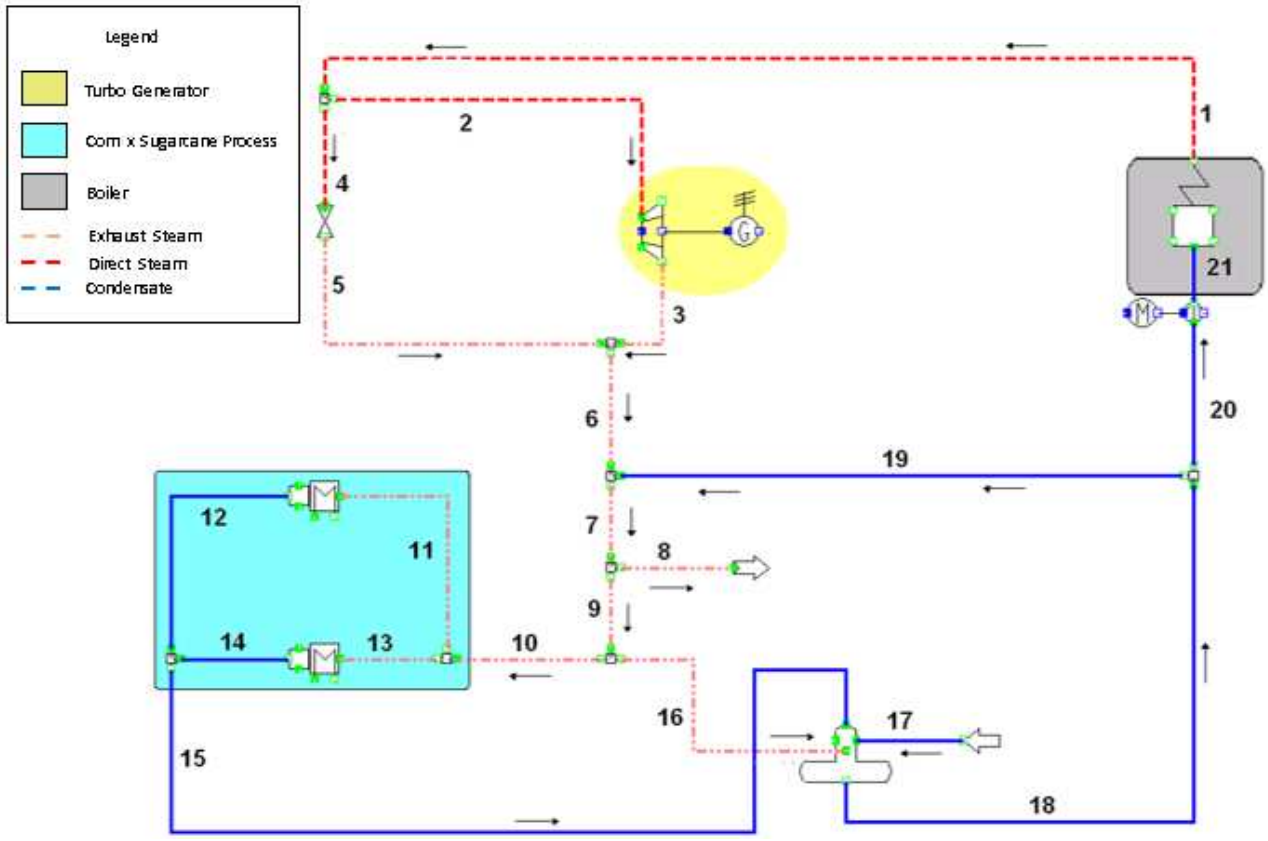


Figure 3 Schematic representation of the plant for Cases 1, 2, and 3, adapted from the author's master's dissertation [44].

3. **Methodological Approaches**

This section describes the thermodynamic and exergoeconomic methodologies applied to evaluate the three operational scenarios presented in Section 2.

The thermodynamic simulations were performed using IPSEpro® (SimTech Simulation Technology, Graz, Austria) [15], a process modeling software that enables steady-state mass and energy balance calculations for the main subsystems, including the boiler, turbine, fermentation, distillation, cogeneration, and co-product production units.

All thermodynamic properties and exergy calculations were determined based on the environmental reference state of 25 °C and 1.013 bar (298.15 K, 101.325 kPa). The exergoeconomic assessment was conducted using EES – Engineering Equation Solver® (F-Chart Software, Middleton, WI, USA) [16], which allows exergy-based costing and the iterative solution of algebraic and thermodynamic equations. The modeling results include first- and second-law efficiencies, component-level exergy destruction, and the distribution of useful and lost exergy flows, which serve as the basis for the subsequent exergoeconomic calculations.

3.1. Thermodynamic Analysis

Initially, the analyses were carried out by defining a control volume (CV) for each equipment unit in the plant. For processes operating at steady state and neglecting kinetic and potential energy variations, the mass, energy, and exergy balance equations are given by Bejan [17], commonly applied in the analysis of energy systems [18,19]. The mass balance ensures the conservation of matter [20], while the energy balance, based on the First Law of Thermodynamics, quantifies heat and work exchanges [21]. Furthermore, exergy analysis, grounded in the Second Law of Thermodynamics, evaluates energy quality and losses due to irreversibilities [22,23], providing a detailed assessment of improvement potential and the actual efficiency of the biorefinery's components [24].

$$\sum_{i=1}^{n} \dot{m}_{in,i} - \sum_{i=1}^{n} \dot{m}_{out,i} = 0 \tag{1}$$

$$\sum_{i-1}^{n} \dot{Q}_{CV} - \dot{W} + \sum_{i-1}^{n} \dot{m}_{\text{in},i} h_{in,i} - \sum_{i-1}^{n} \dot{m}_{out,i} h_{out,i} = 0 \tag{2}$$

$$\sum_{i-1}^{n} \dot{Q}_i \left(1 - T_0 / T_i\right) - \dot{W}_{cv} + \sum_{i-1}^{n} \dot{m}_{in,i}\, ex_{in,i} - \sum_{i-1}^{n} \dot{m}_{out,i}\, ex_{out,i} = \dot{I}_{cv} \quad . \tag{3}$$

Where: $\dot{m}_{in}$ is the mass flow rate entering the control volume (CV) (kg/s), $\dot{m}_{out}$ is the mass flow rate leaving the CV (kg/s), h_{in} is the specific enthalpy at the CV inlet (kJ/kg), h_{out} is the specific enthalpy at the CV outlet (kJ/kg), ex_{in} is the specific exergy at the CV inlet (kJ/kg), ex_{out} is the specific exergy at the CV outlet (kJ/kg), T_i is the surface temperature of the CV (K), T_0 is the reference state fluid temperature (K), $\dot{I}_{CV}$ is the irreversibility rate within the CV (kW), $\dot{Q}_{CV}$ is the heat transfer rate into the CV (kW), and $\dot{W}_{CV}$ is the power associated with the CV (kW).

For the calculation of the specific exergy of a stream ex_f, the following equation can be used [25]:

$$ex_f = \left(h - h_0\right) - T_0 \left(s - s_0\right) + \sum \left(\mu_i - \mu_{0,i}\right) x_i \tag{4}$$

where: h – Specific enthalpy of the vapor (kJ/kg); s – Specific entropy of the vapor (kJ/kg·K); h_0 Enthalpy of water at the reference state (kJ/kg); s_0 – Entropy of water at the reference state (kJ/kg·K); $\mu_{0,i}$ – Chemical potential of the element at the reference state (P_0 , T_0); – Chemical potential of the element in the mixture (P_0 , T_0); x_i – Mole fraction of the component in the mixture.

The specific exergy of bagasse ($ex_{(bag)}$) is calculated using the equation proposed by Szargut, Morris, and Steward [26], which is a methodology widely accepted in the exergy analysis of solid fuels [27,28]. This approach considers the elemental composition of bagasse, including carbon, hydrogen, oxygen, nitrogen, sulfur, and ash, to determine its maximum work potential [29,30]. An accurate assessment of bagasse exergy is crucial for a rigorous evaluation of the boiler and cogeneration system efficiencies within the biorefinery.

$$ex_{bag} = \beta (LHV_{bag} + L_{water} Z_{water}) + ex_{water} Z_{water} \tag{5}$$

where: β is a function of the mass fractions of the bagasse components (%); is the mass fraction of the chemical elements (%); Z_{water} is the mass fraction of water in bagasse (%); L_{water} is the enthalpy of vaporization of water (kJ/kg) and ex_{water} is the chemical exergy of liquid water (kJ/kg).

$$\beta = \frac{\left\{1{,}0412 + 0{,}2160\left(Z_{H_2}/Z_C\right) - 0{,}2499\left(Z_{O_2}/Z_C\right)\left[1 + 0{,}7884\left(Z_{H_2}/Z_C\right)\right] - 0{,}0450\left(Z_{N_2}/Z_C\right)\right\}}{\left[1 - 0{,}3035\left(Z_{O_2}/Z_C\right)\right]} \tag{6}$$

in which: β is the correction factor as a function of the elemental composition of bagasse.

The First Law efficiency of the turbine (η_I) was defined by comparing the actual work obtained with the work that would be produced in a reference isentropic process, for the same discharge pressure, as expressed in:

$$\eta_I = \frac{\dot{W}_{cv}}{\dot{W}_{is}} = \frac{h_{in} - h_{out,real}}{h_{in} - h_{out,is}} \tag{7}$$

Where h_{in} is the inlet enthalpy, $h_{out,real}$ is the real outlet enthalpy, and $h_{out,is}$ is the isentropic outlet enthalpy calculated for the same discharge pressure. Here, $\dot{W}_{cv}$ represents the control volume work of the turbine. This procedure prevents the efficiency from being unity by definition and is consistent with standard practice for expansion machines.

Associated with the use of exergy analysis is the Second Law of Thermodynamics (η_{II}). This concept involves comparing the rate of actual work transfer produced in the process with the variation of exergy evaluated between the real inlet state and the real outlet state, as follows:

$$\eta_{II} = \dot{W}_{vc} / \dot{m}\left(ex_{in} - ex_{out}\right) \tag{8}$$

In the specific case of boilers, the First- and Second-Law efficiencies are calculated, respectively, as:

$$\eta_I = (\dot{m}_{out} h_{out} - \dot{m}_{in} h_{in}) / \dot{m}_{bag} LHV_{bag} \tag{9}$$

$$\eta_{II} = (\dot{m}_{out} ex_{out} - \dot{m}_{in} ex_{in}) / \dot{m}_{bag} ex_{bag} \tag{10}$$

Where: h_{out} – specific enthalpy at the boiler outlet (kJ/kg); h_{in} – specific enthalpy at the boiler inlet (kJ/kg); ex_{out} – specific exergy at the boiler outlet (kJ/kg); ex_{in} – specific exergy at the boiler inlet (kJ/kg); ex_{bag} – specific exergy of bagasse (kJ/kg); $\dot{m}_{out}$ – mass flow rate at the boiler outlet (kg/s); $\dot{m}_{in}$ – mass flow rate at the boiler inlet (kg/s); $\dot{m}_{bag}$ mass flow rate of bagasse consumed in the boiler (kg/s); LHV_{bag} – lower heating value of bagasse (kJ/kg).

3.1.2. Performance Indices Based on the First Law of Thermodynamics

In cogeneration energy conversion systems, performance can be evaluated using different indices based on the First Law of Thermodynamics [31,32]. These indices provide crucial information on fuel utilization efficiency and the relationship between the useful energy generated (electrical and thermal) and the primary energy consumed [32,33]. They quantify the effectiveness of energy conversion and the distribution of the generated energy among different useful forms [34]. The analysis of these parameters is fundamental for optimizing the operation of cogeneration plants and assessing their potential for energy savings.

$$FUE = \left(\dot{W}_{total} + \dot{Q}_{useful}\right) \Big/ \left(\dot{m}_{bag} LHV_{bag}\right) \tag{11}$$

$$EEC = 1 - \dot{m}_{bag} LHV_{bag} \Big/ \left(\dot{W}_{total} / \eta_{therm\text{-}ref} + \dot{Q}_{useful} / \eta_{boiler\text{-}ref}\right) \tag{12}$$

$$IGP = \dot{W}_{total} \Big/ \left(\dot{m}_{bag} LHV_{bag} - \dot{Q}_{useful} / \eta_{boiler}\right) \tag{13}$$

$$RPC = \dot{W}_{total} \Big/ \dot{Q}_{useful} \tag{14}$$

Where: FUE – Fuel Utilization Factor; EEC – Energy Economy due to Cogeneration; IGP – Power Generation Index; RPC – Power-to-Heat Ratio; $\dot{W}_{total}$ – total power output (electrical + mechanical) (kW); $\dot{Q}_{useful}$ – useful thermal power (kW); $\dot{m}_{bag}$ – bagasse mass flow rate (kg/s); LHV_{bag} – lower heating value (kJ/kg); η_{boiler} – boiler thermal efficiency (%); $\eta_{boiler\text{-}ref}$ – thermal efficiency of a reference boiler producing saturated steam (77%); $\eta_{therm\text{-}ref}$ – thermal efficiency of a reference power plant (40%).

3.1.3. Key parameters in sugarcane-based plants

There are some key parameters in sugarcane-based plants, which are associated with the production or consumption of steam and electricity, as well as with the amount of bagasse (or crushed sugarcane) [35, 36]. These parameters are defined as follows:

$$R_{bag-steam} = \dot{m}_{bag} / \dot{m}_{steam} \quad (15)$$

$$R_{steam-cane} = \dot{m}_{steam} / \dot{m}_{cane} \quad (16)$$

$$R_{pow-cane} = \dot{W}_{ele} / \dot{m}_{cane} \quad (17)$$

$$R_{steam-pow} = \dot{m}_{steam} / \dot{W}_{ele} \quad (18)$$

$$R_{bag-pow} = \dot{m}_{bag} / \left(\dot{W}_{ele} + \dot{W}_{mec} \right) \quad (19)$$

Where: $R_{bag-steam}$ – ratio of bagasse consumed to steam produced [–]; $R_{steam-cane}$ – ratio of steam produced to cane consumed [–]; $R_{pow-cane}$ – ratio of electric power generated to cane consumed [kWh/kg]; $R_{steam-pow}$ – ratio of steam consumed to electric power generated [kg/kWh]; $R_{bag-pow}$ – ratio of bagasse consumed to total power produced (electric + mechanical) [kg/kWh].

The overall annual efficiency of the plant can be expressed by the following yield equation:

$$\eta_{overall} = \frac{E_{out}}{E_{in}} \quad (20)$$

Where the output energy (E_{out}) is composed of the sum of the energy from sugarcane ethanol ($E_{ethanol_cane}$), the energy from corn ethanol ($E_{ethanol_corn}$), the electrical energy generated and sold ($E_{electric}$), and the energy from corn co-products ($E_{co-products_corn}$), when applicable. The input energy (E_{in}) corresponds to the energy contained in the processed sugarcane (E_{cane}) and in the corn used (E_{corn}). Therefore, the complete equation would be:

$$\eta_{overall} = \frac{E_{ethanol_cane} + E_{ethanol_corn} + E_{electric} + E_{co-products_corn}}{E_{cane} + E_{corn}} \quad (21)$$

Each energy term in Equation (21) was calculated to ensure methodological transparency and reproducibility by combining the mass flow rates obtained from IPSEpro® process simulations based on industrial design parameters [15] with their respective Lower Heating Values (LHV).

The input energy terms, E_{cane} and E_{corn}, represent the total chemical energy entering the biorefinery through the feedstocks. These values were estimated using LHV parameters consistent with the Brazilian bioenergy sector (4.70 MJ/kg for sugarcane and 15.64 MJ/kg for corn grain), as reported by Dias et al. [2] and Donke [10], and aligned with values commonly reported for biomass fuels in the literature [53]. Production conditions were considered in accordance with the official parameters for the 2024/25 harvest [1].

The energy associated with ethanol production ($E_{ethanol_cane}$ and $E_{ethanol_corn}$) was determined using an LHV of 26.80 MJ/kg, a standard value for hydrous ethanol widely adopted in thermodynamic assessments [21,26]. The term $E_{electric}$ represents the net surplus electricity exported to the grid; for the efficiency calculation, this electrical energy was converted to thermal units using the physical equivalence of 1 kWh = 3.6 MJ, ensuring consistency within the overall energy balance [17,18].

Finally, $E_{co-products_corn}$ accounts for the chemical energy contained in corn co-products, specifically DDGS and crude corn oil. These contributions were estimated from annual production rates and representative industrial calorific values (21.30 MJ/kg for

DDGS and 39.80 MJ/kg for corn oil) reported for integrated flexible plants in the Brazilian context [3,13]. Thus, all energy contributions are expressed on a consistent energetic basis, enabling a transparent and robust evaluation of the system's overall annual efficiency.

This equation quantifies the overall annual conversion of the energy contained in the feedstocks into value-added products and electricity.

3.2 Thermoeconomic Analysis

Thermoeconomic analysis, also known as exergoeconomic analysis, is a powerful and rigorous methodology for evaluating complex energy systems, integrating the principles of the Second Law of Thermodynamics with economic fundamentals [5,6,37,38]. This approach enables the quantification and monetization of internal process irreversibilities through exergy destruction, directly correlating them with the costs of the generated energy or chemical products.

Unlike traditional economic analyses—which are limited to mass and energy balances—exergoeconomic analysis allows detailed traceability of energy resource utilization, including heat, work, and material flows. It also enables the precise allocation of the impacts of internal irreversibilities on the cost of each final product. This capability is particularly relevant in flex biorefineries, which operate with multiple integrated routes (such as sugarcane and corn) and simultaneously produce several products, including ethanol, DDGS, corn oil, and bioelectricity [14,39,40].

In this work, the Exergy Cost Theory (ECT) proposed by Valero et al. [6] was applied. This theory is based on two postulates: (i) the conservation of exergetic costs in each system component and (ii) the proportionality between the unit cost of a flow and its exergy. According to this approach, the cost of a flow equals the sum of the costs of the resources from which it originates plus the cost of the exergy destroyed in the conversion process. This theoretical framework enables the disaggregation of internal costs and the identification of critical points of systemic inefficiency [38,40].

To solve the system of exergoeconomic equations, the extraction method was adopted, which is suitable for systems of high complexity and multiple products, such as those found in cogeneration plants and hybrid biorefineries [8,14,39]. This method is compatible with other advanced formulations, such as the SPECO (Specific Exergy Costing) methodology [25,41], which has also been applied in comparative studies of thermoeconomic and exergoeconomic configurations in biofuel production systems [42]. The exergoeconomic framework adopted in this study follows the principles established by Tsatsaronis and Morosuk [37], whose advanced exergy-based approaches provide a rigorous foundation for cost allocation and system diagnosis. Furthermore, this formulation can be complemented by the hybrid EQC (Exergy-based Quantitative Costing) methodology, which integrates exergy, economics, and environmental sustainability to enhance the assessment of complex energy systems [43].

$$C_Z = \sum (c_{f,k}.\dot{E}_{f,k}) + Z_k + c_{dest,k}.\dot{E}_{dest,k} \quad (22)$$

The equation presented expresses the calculation of the total exergoeconomic cost (C_Z) of a component in an energy plant, combining the costs associated with the input exergy, capital and operating investments, and losses due to irreversibilities. The first term, $\sum (c_{f,k}.\dot{E}_{f,k})$,represents the cost of the exergy flows feeding the component, weighted by the unit cost of each flow. The second term, Z_k, refers to the annualized cost of capital and equipment operation, including investments, maintenance, and other fixed charges. Finally, the term $c_{dest,k}.\dot{E}_{dest,k}$ incorporates the economic impact of internal exergy losses, reflecting the irreversible degradation of useful energy during the operation of the component.

This formulation allows for a technical association between thermodynamic performance and economic cost, providing a solid basis for identifying bottlenecks, optimizing resource utilization, and improving the overall economic efficiency of the plant.

Studies in the field have shown that the combined use of exergoeconomic tools enhances operational decision-making and thermoenergetic optimization in biomass-based energy systems [40,44]. These insights are directly applicable to flex biorefineries, where multi-feedstock operation requires continuous assessment of exergy–cost interactions.

The proper allocation of costs to the products—ethanol, bioelectricity, DDGS, and corn oil—allows the identification of the subsystems that most influence technical performance and economic outcomes. In cogeneration-based biorefineries, exergy destruction in boilers and turbines typically represents a major fraction of the total exergoeconomic cost, making these components key targets for improvement [6,8].

The relevance of exergoeconomic analysis for the optimization of integrated biorefineries is well established. Soltanian et al. [39] demonstrated that exergoeconomic assessment is highly effective in identifying cost-intensive units and exergy-destruction hotspots—particularly in steam generation and cogeneration subsystems—thereby supporting targeted modifications that reduce the production costs of key bio-products. Complementary findings from Effatpanah et al. [45] confirmed the usefulness of combined energy, exergy, and exergoeconomic indicators for prioritizing improvements in biomass-based conversion cycles, including waste-heat-driven ORC systems. Within this context, the biorefinery concept has been recognized as a strategic framework for integrating multiple conversion pathways and enhancing overall system efficiency, as discussed by Cherubini [46], reinforcing the importance of combined thermodynamic and economic assessments to support technological selection and process integration.

Thus, the application of exergoeconomic analysis in this study not only complements the thermodynamic evaluation presented earlier but also provides a solid foundation for strategic decision-making, guiding interventions that maximize the plant's energy and economic return under each proposed operational scenario.

3.2.1. Exergoeconomic Balance Equations

The exergoeconomic analysis of each component of the plant is based on the exergy cost balance, as described by the Exergy Cost Theory [6]. This methodology is formalized from the principles of thermodynamics and exergy accounting, as detailed in the classical formulations of Bejan, Tsatsaronis, and Moran [5] and in the advanced exergy-based methods developed by Tsatsaronis and Morosuk [37]. For a generic component, the exergoeconomic balance can be represented as follows:

$$\sum c_{in}.\dot{E}_{in} + Z_k = \sum c_{out}.\dot{E}_{out} \tag{23}$$

Where c_{in} and c_{out} are the unit costs of the inlet and outlet exergy flows, respectively [BRL MJ^{-1}], $\dot{E}_{in}$ and $\dot{E}_{out}$ are the inlet and outlet exergy flow rates [kW], and Z_k represents the annualized capital and operating cost assigned to the component [BRL s^{-1}].

The exergy destruction in each component ($\dot{E}_{dest,k}$) must also be considered in the balance. The cost of the destroyed exergy can be allocated proportionally among the process products based on their exergy flows or operational priorities [5,6,25]. The simultaneous solution of the set of equations for all plant components allows obtaining the exergoeconomic costs of each final and intermediate product stream, resulting in a detailed evaluation of the economic impact of irreversibilities.

3.2.2. Analysis of Component Capital Costs

The exergoeconomic evaluation of an energy system requires, among other parameters, the estimation of the annualized capital costs of the main equipment. These values are essential for determining the total exergoeconomic cost of each component, as established in the equation presented in Section 3.2.1. Table 4 presents the estimated acquisition costs of the major equipment of the flex biorefinery, based on literature data and calculated using the cost estimation methodology adapted from Rocha [44], which incorporates industrial design parameters and scaling correlations commonly applied to bioenergy systems.

Table 4 Estimated acquisition costs of the major equipment considered in the exergoeconomic model.

	Equipment	Estimated Cost (BRL)
1	Boiler – 43 kgf/cm²	22,477,000.00
2	Backpressure turbine	6,743,100.00
3	Boiler feed pump	423,936.00
4	Sugarcane processing unit	14,500,000.00
5	Corn processing unit	9,100,000.00
6	Deaerator	2,922,010.00
7	Pressure-reducing valve	50,000.00

Investments in these key equipment items enable the integrated operation of ethanol production routes from sugarcane and corn, supporting continuous plant operation and enhanced energy utilization. The sugarcane processing block comprises conventional units for fibrous biomass conversion, including milling systems, evaporators, distillation columns, condensers, shredders, automation systems, and storage tanks. The corn processing block includes the main technologies required for starch conversion, such as liquefaction and saccharification reactors, milling systems, centrifuges, evaporators, and oil recovery units. Together, these process structures form the industrial basis for the thermodynamic and exergoeconomic assessments conducted in this study.

Grouping the equipment into distinct blocks reinforces process modularization, allowing for the systematic organization of technical and economic data by production route, avoiding duplication in shared units (such as automation), and enabling a clearer comparative analysis. This approach is frequently adopted in integrated biorefinery assessments, as discussed by Pérez Almada et al. [4].

The deaerator, turbine, and pump complete the support components of the cogeneration system. Although they represent relatively lower costs, these items have a significant impact on the system's energy performance and the quality of the generated steam. The pressure-reducing valve, despite its marginal cost, is essential for controlling the process supply pressure.

To complement the exergoeconomic analysis of the plant, the annualized capital costs of the main components were estimated and directly incorporated into the exergoeconomic balance equations. Based on the initial investment values of each piece of equipment, as presented in Table 4, the costs were annualized following the methodology proposed by Pellegrini and Oliveira Jr. [8], considering an internal rate of return of 12% per year and an average service life of 20 years, according to the nature and function of each item.

The annual cost for capital amortization, operation, and maintenance (Ca) from Table 5 was calculated using the following equation:

$$Ca = Inv.(f_a + f_{omf} + FC.f_{omv}) \tag{24}$$

Where Ca is the annual cost of capital amortization, operation, and maintenance [BRL year^{-1}], Inv is the investment cost of the equipment [BRL], f_a is the amortization factor (fraction per year), f_{omf} is the fixed operation and maintenance cost factor (fraction per year), f_{omv} is the variable operation and maintenance cost factor (fraction), FC is the load factor (–), and T_o is the effective annual operating time [h/year].

For the application of Equations (24) and (25), the following parameters were adopted: amortization factor f_a=0.1344 (corresponding to an annual interest rate of 12% and a service life of 20 years), fixed operation and maintenance cost factor f_{omf}

=0.09 (fraction per year), variable operation and maintenance cost factor f_{omv} =0.01 (fraction), load factor FC =0.75, and effective annual operating time T_o=7,680 h/year. These values were consistently applied to all equipment and operational scenarios considered in this study.

Table 5 Annual costs with amortization of the main equipment of the plant.

	Equipment	Estimated Cost (BRL)
1	Boiler – 43 kgf/cm²	5,212,416.30
2	Backpressure turbine	1,563,724.89
3	Boiler feed pump	98,310.76
4	Sugarcane processing unit	3,362,550.00
5	Corn processing unit	2,110,290.00
6	Deaerator	677,614.12
7	Pressure-reducing valve	11,595.00

With the annualized values obtained, it was possible to determine the unit exergoeconomic cost of each piece of equipment per second of continuous operation, using the equation and represented in Table 6:

$$Z = \frac{C_a}{T_o.3600} \tag{25}$$

This conversion made it possible to directly associate the annual costs with the plant's thermodynamic model, facilitating the integration with the exergy flows in each component.

Table 6 Unit exergoeconomic costs per second (Z_k).

	Equipment	Estimated Cost (BRL)
1	Boiler – 43 kgf/cm²	0.1883
2	Backpressure turbine	0.0565
3	Boiler feed pump	0.0036
4	Sugarcane processing unit	0.1215
5	Corn processing unit	0.0762
6	Deaerator	0.0245
7	Pressure-reducing valve	0.0004

The Z_k values obtained were incorporated into the exergoeconomic balance equations of each component, as described previously. This approach allows capital costs to be treated not as external data to the system but as parameters directly integrated into the analysis of irreversibilities and exergy flows, thereby ensuring greater precision and robustness in evaluating the economic performance across the plant's different operational scenarios.

For the thermoeconomic analysis conducted in this study, a reference value of 180.00 BRL t^{-1} (Brazilian Real per tonne) for sugarcane bagasse was adopted for the 2025 harvest. This value was derived from price ranges observed in Brazilian agricultural marketplace listings compiled by MF Rural, which reflect real transactions between producers and buyers across major producing regions [47]. The selected value falls within the range commonly observed in traditional sugarcane-producing states such as São Paulo, Mato Grosso do Sul, and Minas Gerais, and is consistent with market tendencies reported by industry sources highlighting

the growing economic relevance of sugarcane bagasse in the bioenergy sector [48]. The adoption of this representative market-based value supports a robust economic assessment while maintaining alignment with current Brazilian conditions for sugarcane biomass.

The price of sugarcane was set at 146.34 BRL t^{-1} based on the Consecana-PR quotation reported by Notícias Agrícolas [49]. For corn, a value of 64.02 BRL per 60 kg bag, equivalent to approximately 1,067.00 BRL t^{-1}, was obtained from the CEPEA/ESALQ–B3 Indicator for the Port of Paranaguá [50].

Among the coproducts, a value of 6,610.00 BRL t^{-1} was adopted for crude corn oil (DDCO), according to industrial quotations provided by Abisa and Editora Stilo during the first half of 2025 [51]. For DDGS (dried distillers grains with solubles), an estimated value of 1,300.00 BRL t^{-1} was considered, consistent with domestic market averages reported in recent sectoral analyses [52].

To convert market prices into exergoeconomic costs—an essential step in solving the system of equations—the specific chemical exergies of each material were estimated from their ultimate analysis and lower heating value using standard correlations for organic fuels. For raw sugarcane, a value of 4.70 MJ kg^{-1} was adopted following methodologies commonly applied in sugarcane biorefinery assessments [7] and Szargut-based correlations [26]. For corn grain, a specific chemical exergy of 15.64 MJ kg^{-1} was estimated from its elemental composition and lower heating value using the same Szargut-based correlations [26], in accordance with methodological approaches applied to thermodynamic assessments of corn-ethanol systems [53]. For sugarcane bagasse, used as the primary fuel in the cogeneration system, a value of 13.00 MJ kg^{-1} (dry basis) was adopted, calculated according to the methodology of Szargut, Morris, and Steward, which relates chemical exergy to elemental composition and lower heating value [26].

For the coproducts of the corn route, specific chemical exergies were determined following the methodology of Szargut et al. [26], which demonstrates that the chemical exergy of dry organic and lipid-based materials can be reliably approximated by their Higher Heating Value (HHV). A specific chemical exergy of 21.30 MJ kg^{-1} was adopted for DDGS, a value consistent with its reported gross energy content [52]. For crude corn oil (DDCO), 39.80 MJ kg^{-1} was adopted, which is in close agreement with reference HHV values for vegetable oils. Experimental data show that common vegetable oils, including corn oil, typically exhibit HHVs in the range of 39–40 MJ kg^{-1} [54], supporting the suitability of the selected exergy value and reinforcing its consistency with the exergy–energy correspondence described by Szargut et al. [26]. Finally, for hydrous ethanol produced from both sugarcane and corn, a specific chemical exergy of 26.80 MJ kg^{-1} was adopted. This value is consistent with the lower heating value (LHV) of pure ethanol compiled in standard thermochemical references such as Çengel and Boles [21] and is widely employed in exergoeconomic analyses of renewable liquid fuels [26].

To determine the unit costs of each energy and product stream, an exergoeconomic model based on the Exergy Cost Theory (ECT) was developed. The model consists of a system of linear equations in which, for each component kkk of the plant, a cost balance equates the cost of inlet exergy flows together with capital and operational costs (Z_k) to the cost of outlet flows. To ensure the solvability of the system, auxiliary equations were formulated following the "Fuel" and "Product" (F and P) principles, as established in the Exergy Cost Theory proposed by Valero, Lozano, and Muñoz [6]. Table 7 presents the complete set of cost-balance and auxiliary equations used in the analysis.

Table 7 Exergy Equations.

Eq	Component / Process	Type of Equation	Equation	Description
E1	Boiler	Cost Balance	$c_{bag}.\dot{E}_{bag} + c_{21}.\dot{E}_{21} + Z_{boiler} = c_1.\dot{E}_1$	The cost of the generated steam (1) is the sum of the costs of the inputs (bagasse, water) and the capital cost.

E2	Splitter	Auxiliary	$c_2 = c_1$	The unit cost of the steam going to the turbine (2) is equal to that of the main steam (1).
E3	Splitter	Auxiliary	$c_4 = c_1$	The unit cost of the steam going to the valve (4) is equal to that of the main steam (1).
E4	Turbine	Cost Balance	$c_2.\dot{E}_2 + Z_{turbine} = c_3.\dot{E}_3 + c_W.\dot{E}_W$	The cost of the inputs (steam, capital) is allocated to the products (exhaust steam and power).
E5	Turbine	Auxiliary	$c_3 = c_2$	Assigns the cost of power generation to the electricity, maintaining the process steam's unit cost.
E6	Pressure-Reducing Valve	Cost Balance	$c_4.\dot{E}_4 + Z_{valve} = c_5.\dot{E}_5$	The cost of the low-pressure steam (5) is the sum of the input steam's cost and the capital cost.
E7	Mixer	Cost Balance	$c_3.\dot{E}_3 + c_5.\dot{E}_5 = c_6.\dot{E}_6$	The costs of the steam streams (3, 5) are summed to define the cost of the combined stream (6).
E8	Steam	Auxiliary	$c_8 = c_6$	The unit cost of the unused steam (8) is the same as that of the distribution header (6).
E9	Steam	Auxiliary	$c_{10} = c_6$	The unit cost of the steam heading to the processes (10) is the same as that of the header (6).
E10	Splitter	Auxiliary	$c_{11} = c_{10}$	The unit cost of the steam for the corn process (11) is equal to that of the distribution stream.
E11	Splitter	Auxiliary	$c_{13} = c_{10}$	The unit cost of the steam for the sugarcane process (13) is equal to that of the distribution stream.
E12	Splitter	Auxiliary	$c_{16} = c_{10}$	The unit cost of the steam for the deaerator (16) is equal to that of the distribution stream.
E13	Corn Block	Cost Balance	$c_{corn}.\dot{E}_{corn} + c_{11}.\dot{E}_{11} + Z_{corn} = c_{ethcorn}.\dot{E}_{ethcorn} + c_{oil}.\dot{E}_{oil} + c_{DDGS}.\dot{E}_{DDGS} + c_{12}.\dot{E}_{12}$	Allocates the costs of raw material, energy, and capital among the corn products.
E14	Corn Block	Auxiliary	$c_{12} = 0$	The returning condensate from the corn process carries no cost.
E15	Corn Block	Auxiliary	$c_{oil} = Market\ Price_{oil} / ex_{oil}$	The cost of the corn oil co-product is defined by its market value.
E16	Corn Block	Auxiliary	$c_{DDGS} = Market\ Price_{DDGS} / ex_{DDGS}$	The cost of the DDGS co-product is defined by its market value.

E17	Sugarcane Block	Cost Balance	$c_{sugarcane}.\dot{E}_{sugarcane} + c_{13}.\dot{E}_{13} + Z_{sugarcane} = c_{ethsugarcane}.\dot{E}_{ethsugarcane} + c_{14}.\dot{E}_{14}$	Allocates the costs of raw material, energy, and capital to the sugarcane ethanol.
E18	Sugarcane Block	Auxiliary	$c_{14} = 0$	The returning condensate from the sugarcane process carries no cost.
E19	Deaerator	Cost Balance	$c_{12}.\dot{E}_{12} + c_{14}.\dot{E}_{14} + c_{16}.\dot{E}_{16} + c_{17}.\dot{E}_{17} + Z_{deaerator} = c_{18}.\dot{E}_{18}$	The cost of the feedwater (18) is the sum of the costs of the input streams and capital.
E20	Feedwater Pump	Cost Balance	$c_{18}.\dot{E}_{18} + Z_{pump} = c_{21}.\dot{E}_{21}$	The cost of the pressurized water (21) is the sum of the input water's cost and the energy.

The exergoeconomic analysis of components with multiple products—such as the Corn Block (E13)—requires auxiliary equations to close the cost system. In this work, we followed the Exergy Cost Theory, which combines cost balances with the postulates of conservation and proportionality and applies the "Fuel" and "Product" (F and P) rules to components with bifurcations and multiple products [6]. Accordingly, E13 distributes the raw material, energy, and capital costs among the corn-derived products, while the auxiliary equations E15 and E16 exogenously set the unit costs of oil and DDGS as "Market Price/ex" (market price divided by specific exergy), following the SPECO principle that allows externally imposed costs for market-valued co-products [25]. In this approach, the coproducts do not have internally determined costs: their market prices are introduced into the model and act as a "credit" that offsets part of the block costs, allowing the exergoeconomic cost of ethanol to be determined as the remaining main product.

After completing the thermodynamic modeling, an exergy analysis was performed for all process streams. The specific physical exergy of each flow was determined from its thermodynamic properties relative to the environmental reference state (T_0 = 25 °C; P_0 = 1.013 bar), according to Equation (4) and the fundamentals of the exergy method [19]. To enable an annual comparison among the three operational scenarios, the exergy flows calculated for the harvest and off-season periods were weighted by the corresponding number of operating days in each period. This weighting procedure yielded the annualized exergy flows (Ė), which represent the average exergy transfer rates over the year and serve as the basis for the subsequent exergoeconomic evaluation. Table 8 summarizes the annualized exergy values for the main process streams and equipment.

Table 8 Annualized Exergy Flows.

Points	Case 1 (kW)	*Case 2 (kW)*	*Case 3 (kW)*
1	*39.62*	*46.90*	*46.90*
2	*6.58*	*46.55*	*13.56*
3	*3.36*	*23.79*	*6.93*
4	*33.02*	*0.35*	*33.34*
5	*23.16*	*0.24*	*23.44*
6	*26.68*	*31.22*	*31.22*
7	*26.89*	*31.32*	*29.73*
8	*10.84*	*11.39*	*2.09*
9	*16.03*	*19.91*	*27.70*
10	*13.91*	*17.55*	*26.31*
11	—	*3.64*	*13.58*
12	—	*0.19*	*0.64*
13	*13.91*	*13.91*	*25.85*
14	*0.56*	*0.56*	*1.17*
15	*0.58*	*0.77*	*1.22*

16	*2.12*	*2.37*	*1.27*
17	*0.04*	*0.04*	*0.01*
18	*1.84*	*2.23*	*2.34*
19	*0.02*	*0.08*	*0.20*
20	*1.81*	*2.15*	*2.15*
21	*1.96*	*2.32*	*2.32*

3.2.3 Analysis of the Cost of Destroyed Exergy

In this stage, the monetary impact of thermodynamic irreversibilities in each component is quantified through the coupling of the exergy balance with the exergoeconomic model. Following the SPECO methodology developed by Lazzaretto and Tsatsaronis [25] and the classical thermoeconomic formulations of Tsatsaronis and Winhold [41], the cost rate associated with the exergy destroyed in component *k* is given by:

$$\dot{C}_{D,k} = c_{F,k}\dot{E}_{D,k} \tag{26}$$

In this expression, $\dot{C}_{D,k}$ is the cost rate of destroyed exergy (BRL h^{-1}), $\dot{E}_{D,k}$ is the exergy destruction rate (GJ h^{-1}) obtained from the Second Law balance, and $c_{F,k}$ represents the unit cost of the exergetic "fuel'' consumed by the component (BRL GJ^{-1}). In accordance with the thermoeconomic definitions proposed by Tsatsaronis and Winhold [41] and consolidated in the SPECO framework by Lazzaretto and Tsatsaronis [25], the exergetic "fuel" refers to the stream that the component utilizes to generate its "product", which does not necessarily coincide with the plant's primary input fuel.

In the present study, the following modeling assumptions were adopted: (i) for the boiler, (c_F) corresponds to the exergy-based cost of bagasse, following the thermoeconomic procedures applied to sugarcane-based cogeneration systems [8,14]; and (ii) for the backpressure turbine and the pressure-reducing valve, (c_F) equals the cost of high-pressure steam (Point 1), as determined within the steam–power subsystem (E1–E7), consistent with prior exergoeconomic analyses of integrated distillation and cogeneration systems [42]. For the turbine, the unit cost of the exhaust steam was assumed equal to that of the inlet steam, so that the additional exergoeconomic cost associated with exergy conversion in the turbine is assigned to electricity generation. Under this assumption, the turbine is treated primarily as an electricity-producing component within the steam–power subsystem, while the exhaust steam acts as an intermediate utility stream supplied to downstream process units. Capital and O&M (operation and maintenance) costs were annualized to obtain the equipment cost rate ($\dot{Z}$), computed according to standard thermoeconomic formulations for cost recovery and amortization [5]. These annualized cost rates were incorporated into the steam subsystem (E1–E7), which provides the unit exergetic costs required to determine (c_P). The numerical application of this methodology is presented in the Results section.

4. **Results and Discussions**

The thermodynamic and exergoeconomic results for the three operational scenarios are discussed in this section, based on the mass and energy balances summarized in Tables 2 and 3. The analysis focuses on how the integration of corn ethanol and the transition to the Flex 360 model (Case 3) optimize the plant's energy profile and cost structure compared to the baseline (Case 1).

The steam flow distribution reveals marked differences in energy management. In Cases 1 and 2, during the harvest season, a substantial fraction of surplus steam is released at point 8, reflecting the limited thermal demand of the active production units. By

contrast, Case 3 demonstrates optimized steam allocation, with nearly all generated steam directed to the simultaneous processing of sugarcane and corn. In the off-season, both Case 2 and Case 3 achieve high efficiency, as steam is almost fully consumed by the corn distillery, underscoring the superior thermodynamic performance of the plant under a flexible operational regime.

4.1 Thermodynamic Results

Table 9 illustrates the evolution of steam utilization across the operational scenarios. During the harvest, steam generation remains constant (159 t/h from 70 t/h of bagasse), but its distribution varies according to the integration level.

Steam utilization in Cases 1 and 2 reveals a significant imbalance between energy generation and process demand. In the baseline (Case 1), 40.8% of the steam (64.9 t/h) is released at point 8 without productive use, even with the distillery at maximum capacity. This inefficiency persists in Case 2; although the flow to cogeneration increases to 157.6 t/h, the surplus remains unchanged, indicating that thermal demand is insufficient to absorb the additional energy.

This landscape changes markedly in Case 3. The integration of the corn ethanol process provides a thermal sink for the excess energy, reducing the surplus steam to only 5.7% (9.1 t/h). This confirms that a second production route with higher thermal demand enables a much more effective utilization of the biomass-derived energy.

During the off-season (Cases 2 and 3), the system continues to operate at high efficiency using stored bagasse. The corn process consumes approximately 97.1% of the generated steam, resulting in residual losses significantly lower than those recorded during the harvest period of non-integrated configurations.

The significant amount of unutilized steam observed in Cases 1 and 2 is partly due to the modeling assumption of a standalone distillery. Without complementary processes like sugar manufacturing to demand additional thermal load, the surplus energy is ultimately released at point 8.

In summary, the progression from Case 1 to Case 3 represents a strategic transition toward an integrated, year-round approach. Case 3 emerges as the most comprehensive configuration, maximizing both biomass utilization and installed plant capacity by balancing energy demand throughout the year.

Table 9 Inputs and Steam.

		Harvest			Off-season		
Product	**Unit**	**Case 1**	**Case 2**	**Case 3**	**Case 1**	**Case 2**	**Case 3**
Bagasse burned	[t/h]	70.0	70.0	70.0	—	31.1	31.1
Steam generated	[t/h]	159.0	159.0	159.0	—	69.2	69.2
Steam to cogeneration	[t/h]	28.44	157.6	157.6	—	69.2	69.2
Steam to sugarcane process	[t/h]	83.3	83.3	83.3	—	—	—
Steam to corn process	[t/h]	—	—	67.2	—	67.2	67.2
Unused steam	[t/h]	64.9	64.9	9.1	—	10.2	10.2

A comparative analysis of the overall plant performance (Table 10) highlights a substantial improvement in energy utilization as operational integration increases. The low annual efficiency observed in Case 1 (25.27%) is fundamentally linked to the production constraints of a seasonal, sugarcane-only model, where a large portion of the bagasse energy is wasted due to the lack of additional processes to absorb surplus steam.

While the inclusion of the corn ethanol route in Case 2 significantly enhances off-season efficiency to approximately 73.5%, its annual performance (46.46%) is still penalized by the lack of diversification during the harvest period. In contrast, Case 3 represents the pinnacle of operational efficiency by maintaining simultaneous sugarcane and corn processing. This integrated

approach effectively doubles the harvest-season efficiency compared to the baseline and achieves an annual overall yield of 61.26% (as detailed in Figure 4).

These results confirm that the presence of diversified energy-demanding routes (corn ethanol, electricity, and co-products) is the determining factor for maximizing the utilization of available biomass energy. Without these integrated pathways, the available energy is ultimately lost as surplus steam, limiting the global efficiency of the biorefinery.

Table 10 Overall plant efficiency for Cases 1, 2, and 3.

Period	Case 1	Case 2	Case 3
Harvest (%)	25.27	28.21	57.93
Off-season (%)	0.00	73.51	73.5

The annual overall efficiency results (Figure 4) were determined as a weighted average of the harvest and off-season periods to accurately capture seasonal variations over the full production cycle. These results underscore the potential of integrated biorefineries (Case 3) to maximize biomass utilization and installed capacity, reaching a significant annual yield of 61.26%.

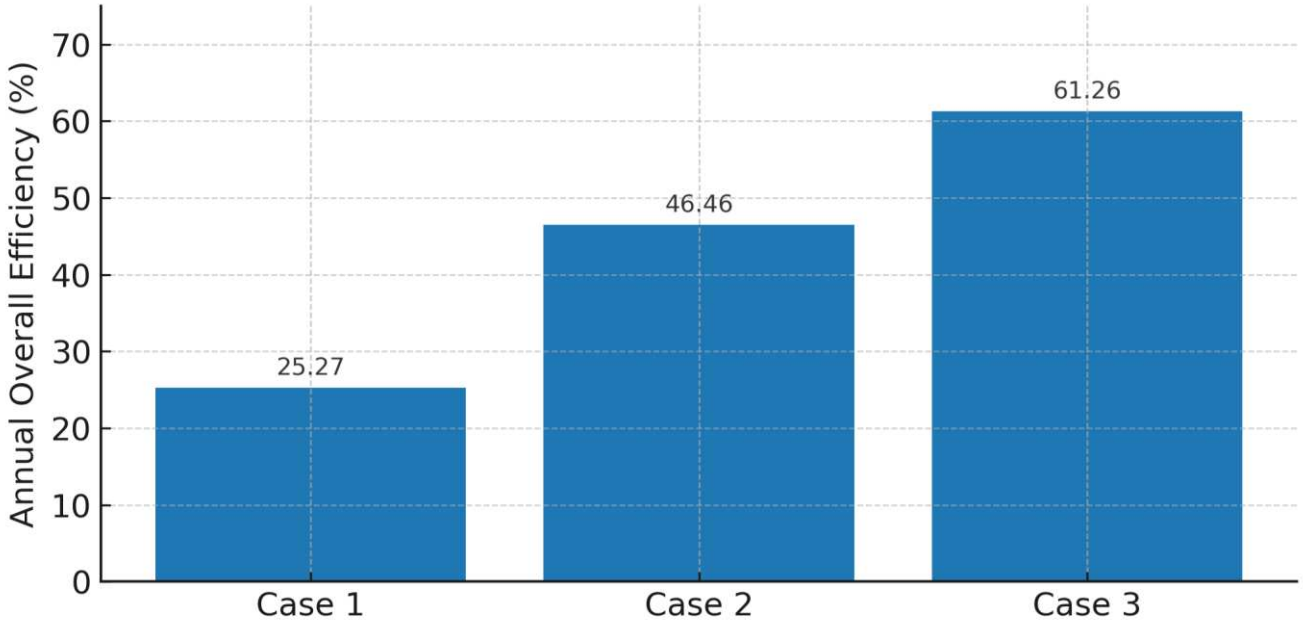


Figure 4 Evolution of Annual Overall Efficiency.

The performance indices summarized in Table 11 indicate a consistent trend toward greater energy autonomy and electricity export capacity across the analyzed configurations. Both the Energy Utilization Factor (FUE) and the Energy Economy due to Cogeneration (EEC) reflect a transition from the unfavorable energy balance observed in Case 1 ($EEC = -0.62$) to a net-energy-producer profile in Case 3 ($EEC = 0.16$). This evolution is primarily associated with the integration of corn processing, which creates more favorable thermodynamic conditions for higher steam utilization and sustained turbine operation throughout the year.

The Power-to-Heat Ratio (RPC) and the specific electricity generation rate ($R_{pow-cane}$) further reinforce this operational shift. The substantial increase in electricity generation between Case 1 and the integrated scenarios confirms a transition from a self-consumption-oriented configuration to one capable of exporting surplus power. Notably, the plant maintains its maximum electricity export rate in Case 3 even after incorporating the additional thermal demand of corn ethanol production, suggesting that the existing

cogeneration infrastructure is sufficiently robust to support expanded operation without compromising energy conversion performance.

Finally, the specific bagasse consumption ($R_{bag-pow}$) reveals an approximately fivefold improvement in conversion efficiency relative to the baseline scenario. This result indicates that the flexible configuration (Case 3) enables more effective biomass utilization, sustaining high thermodynamic performance despite the increased complexity associated with integrated production routes.

Table 11 Plant Performance Indices and Parameters.

Index	Description	Harvest Season			Off-Season		
		Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
$\eta_{overall}$	Overall efficiency (%)	25.27	28.21	57.93	—	73.51	73.51
FUE	Fuel Utilization Factor	0.45	0.51	0.76	—	0.74	0.74
EEC	Energy Economy due to Cogeneration	-0.62	-0.15	0.16	—	0.77	0.77
IGP	Power Generation Index	0.03	0.16	0.16	—	0.16	0.16
RPC	Power-to-Heat Ratio	0.07	0.48	0.28	—	0.28	0.28
$R_{bag-steam}$	Bagasse-to-Steam Ratio	0.44	0.44	0.44	—	0.19	0.19
$R_{steam-cane}$	Steam-to-Cane Ratio	0.48	0.48	0.48	—	—	—
$R_{pow-cane}$	Power per Cane	12.60	75.00	75.00	—	—	—
$R_{steam-pow}$	Steam per Electricity	6.60	6.30	6.30	—	6.30	6.30
$R_{bag-pow}$	Bagasse per Power	0.03	0.006	0.006	—	0.014	0.014

The ethanol production results summarized in Table 12 highlight the strong influence of operational strategy on the utilization of installed capacity throughout the year. In Case 1, ethanol production is entirely constrained by the seasonal availability of sugarcane, leading to substantial idle capacity during the off-season. Case 2 partially mitigates this limitation by extending plant operation through off-season corn ethanol production, resulting in a significant increase in total annual output.

The most pronounced gains are observed in Case 3, where the simultaneous processing of sugarcane and corn during the harvest season, followed by continued corn ethanol production in the off-season, enables near-continuous plant operation. This integrated configuration yields an annual ethanol production approximately five times greater than the baseline scenario and more than twice that achieved in Case 2. These results demonstrate that the combined integration of feedstocks and year-round operation is the most effective strategy for maximizing ethanol output while optimizing the utilization of existing industrial infrastructure.

Table 12 Ethanol production (m^3).

	Harvest Season	Off-Season	Annual
Case 1	161,998.4	—	161,998.4
Case 2	161,998.4	207,738.4	369,736.8
Case 3	654,010.4	207,738.4	861,748.8

The turbine power results (Table 13) reflect a transition toward higher capacity utilization and export-oriented cogeneration. In the baseline scenario (Case 1), the 25 MW turbine operates at a markedly low capacity factor, supplying only the plant's internal demand during the harvest season. In contrast, the integrated configurations (Cases 2 and 3) operate at full nominal capacity during the harvest, enabling substantial electricity exports to the grid.

During the off-season, sustained power generation is supported by steam produced from stored bagasse, ensuring near-continuous operation of the cogeneration system. This operational evolution significantly improves the utilization of installed assets

and contributes to the dilution of capital costs. Consequently, the integrated scenarios exhibit enhanced thermodynamic efficiency and stronger thermoeconomic performance on an annual basis.

Table 13 Turbine power (kW).

	Harvest Season	Off-Season
Case 1	4,512.0	—
Case 2	25,000.0	10,979.6
Case 3	25,000.0	10,979.6

The annual production portfolio summarized in Table 14 quantifies the operational gains enabled by feedstock integration and continuous plant utilization. The baseline configuration (Case 1) is constrained by the seasonal nature of sugarcane, limiting production to 161,998.4 m³ of hydrous ethanol and resulting in idle industrial capacity during the off-season.

Extending operation through corn processing (Case 2) more than doubles annual ethanol output while introducing high-value co-products, including DDGS and crude corn oil, and generating a substantial electricity surplus. The fully integrated configuration (Case 3) achieves the highest level of asset utilization, producing 861,748.8 m³ of ethanol alongside significant volumes of co-products.

Although Case 3 exports slightly less electricity than Case 2 due to the additional thermal demand of simultaneous corn processing during the harvest, the configuration maximizes total product generation and revenue potential. This trade-off reflects a strategic shift from an electricity-surplus-oriented operation toward a diversified biorefinery model focused on higher overall value creation.

Table 14 Annual production

Production	Case 1	Case 2	Case 3
Hydrous ethanol (m³)	161,998.4	369,736.8	861,748.8
Dried distillers' grains (DDGS) (t)	—	157,776	531,456
Crude corn oil (t)	—	7,888.8	26,572.8
Surplus electricity (MWh)	—	125,428	101,063

4.2 Exergoeconomic Assessment

The exergoeconomic assessment summarized in Table 15 provides a detailed mapping of cost formation by integrating thermodynamic inefficiencies with capital investment requirements. The results indicate a substantial reduction in the unit production cost of sugarcane ethanol, decreasing from 1.90 BRL L^{-1} in Case 1 to 1.42 BRL L^{-1} in Case 3. This 25% reduction is primarily associated with improved exergy utilization, enhanced steam management, and the dilution of fixed costs enabled by year-round operation.

To provide market context, hydrous ethanol in São Paulo was priced at approximately 2.54 BRL L^{-1} in July 2025. The gap between market price and modeled production cost suggests favorable economic conditions for integrated operation, although a full financial analysis is beyond the scope of this study.

The corn ethanol pathway also demonstrates competitive production costs, stabilizing near 1.39–1.40 BRL L^{-1}. Additionally, revenue diversification through high-value coproducts—such as DDGS and crude corn oil—improves the economic robustness of the system by distributing costs across multiple product streams and reducing exposure to ethanol price volatility.

Overall, the results support the thermoeconomic attractiveness of integrated sugarcane–corn biorefineries and highlight the role of operational flexibility in enhancing cost efficiency.

Table 15 Final Exergoeconomic Cost of Products by Operational Scenario.

Product	Unit	Case 1	Case 2	Case 3
Sugarcane Ethanol	BRL GJ^{-1}	87.59	67.97	65.45
	BRL L^{-1}	1.90	1.48	1.42
Corn Ethanol	BRL GJ^{-1}	—	64.62	64.13
	BRL L^{-1}	—	1.40	1.39
Surplus Electricity	BRL GJ^{-1}	29.74*	17.41	16.75
	BRL MWh^{-1}	107.07*	62.69	60.31
DDGS (Feed)	BRL GJ^{-1}	—	61.03	61.03
	BRL t^{-1}	—	1,300.00	1,300.00
Corn Oil (DDCO)	BRL GJ^{-1}	—	166.08	166.08
	BRL t^{-1}	—	6,610.00	6,610.00

*Theoretical internal cost; no surplus available for sale.

The production cost of surplus electricity (Figure 5) further illustrates the benefits of the integrated operational model. Based on the turbine exergoeconomic balance (Eq. 23), a substantial cost reduction is observed, with the unit electricity cost decreasing from 107.07 BRL MWh^{-1} in Case 1 to 60.31 BRL MWh^{-1} in Case 3, corresponding to a 43.7% reduction. This improvement is primarily associated with the near-continuous operation of the 25 MW turbine, which enhances the dilution of capital investment and operation and maintenance costs over a larger annual energy output.

These results indicate a high level of competitiveness when compared with Brazilian electricity market benchmarks. Although the spot price (PLD) for 2025 may occasionally approach the regulatory lower bound of 58.60 BRL MWh^{-1} [55], the exergoeconomic production costs remain well below typical forward contract prices in the free-contracting market (ACL), which may exceed 300 BRL MWh^{-1} depending on the contract period [56]. This comparison supports the economic viability of export-oriented cogeneration in the integrated scenarios (Cases 2 and 3), even under conservative market conditions.

Ultimately, the simultaneous reduction in the production costs of both electricity and ethanol reinforces the financial robustness of the Flex 360 configuration. By maximizing the utilization of installed industrial assets and minimizing thermodynamic inefficiencies, the integrated biorefinery achieves a more competitive position within the Brazilian bioenergy and cogeneration context.

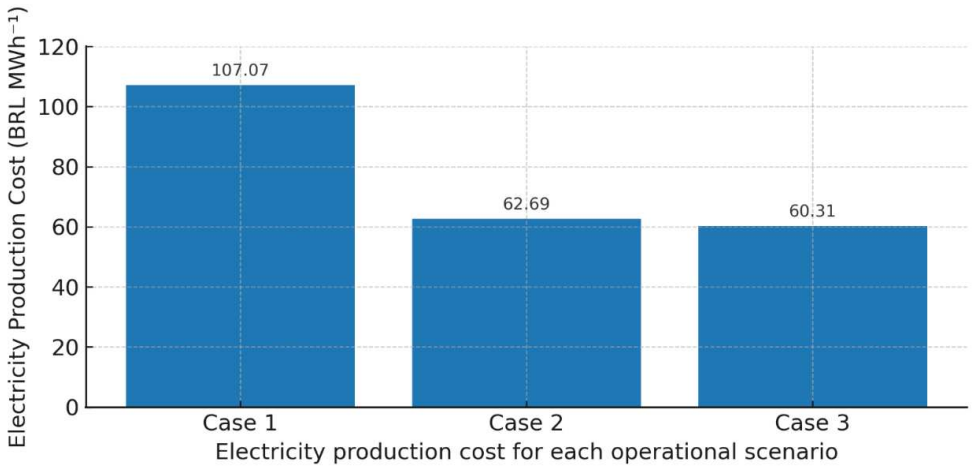


Figure 5 Electricity Production Cost (BRL MWh⁻¹) by Scenario

Table 16 presents the exergoeconomic costs of the main internal utilities, obtained from the solution of the component cost balances, in which thermodynamic inefficiencies are explicitly translated into economic penalties. The transition from Case 1 to the integrated configurations (Cases 2 and 3) results in a reduction of approximately 44% in the unit costs of high-pressure steam and pressurized feedwater. This improvement is primarily associated with the more continuous operation of the cogeneration system, which enhances asset utilization and allows the allocation of fixed capital and O&M costs over a higher energetic throughput.

A critical insight is provided by the cost of low-pressure process steam (Point 6). In Case 1, its unit cost (41.90 BRL GJ⁻¹) exceeds that of the high-pressure steam from which it is derived (29.74 BRL GJ⁻¹). This apparent contradiction represents a direct monetary quantification of exergy destruction associated with the pressure-reducing valve, which performs an isenthalpic expansion without producing useful work. Within the exergoeconomic framework, the cost of the destroyed exergy is allocated to the outgoing stream, inflating its unit cost.

In contrast, for Cases 2 and 3, the cost at Point 6 stabilizes near the main steam cost (18.00–18.43 BRL GJ⁻¹), since most of the pressure reduction occurs through the turbine, where exergy is converted into useful electricity and internal losses are minimized. These results demonstrate that exergy preservation is not merely a thermodynamic objective, but a primary economic driver in integrated biorefineries, directly influencing the unit cost of utilities and, consequently, the competitiveness of the final products.

Table 16 Exergoeconomic Cost of Internal Utilities

Internal Utility / Stream	Point (Figure 3)	Unit	Case 1	Case 2	Case 3
High-Pressure Steam	1	BRL GJ⁻¹	29.74	17.41	16.75
Process Steam (Low Pressure)	6	BRL GJ⁻¹	41.90	18.00	18.43
Feedwater (Pressurized)	21	BRL GJ⁻¹	23.42	18.05	18.65

The exergoeconomic analysis (Table 17) quantifies the monetary impact of thermodynamic irreversibilities in key components. Case 1 exhibits the highest total inefficiency cost (12,256.23 BRL h⁻¹), primarily driven by boiler combustion irreversibilities and significant throttling losses in the pressure-reducing valve (PRV).

The transition to the integrated scenarios (Cases 2 and 3) results in substantial system-wide optimization, reducing total inefficiency costs by approximately 32% (~3,879 BRL h⁻¹). The most impactful improvement is the near-elimination of PRV-related

losses, which decline from 1,505.23 BRL h^{-1} to less than 7.00 BRL h^{-1}, achieved by redirecting steam from dissipative throttling to productive turbine expansion.

Although the turbine's absolute inefficiency cost increases in the integrated configurations—reflecting higher utilization and power generation—this represents a favorable thermoeconomic trade-off. The additional exergy destruction associated with turbine operation is economically negligible compared to the substantial savings obtained by minimizing valve-induced losses.

Overall, the results identify steam-flow reconfiguration as a primary thermoeconomic lever for reducing the financial penalties associated with energy degradation in integrated biorefineries.

Table 17 Hourly Cost of Exergy Losses by Scenario

Component	Parameter	Unit	Case 1	Case 2	Case 3
Boiler	Destroyed Exergy	GJ/h	774.42	599.62	599.62
	Fuel Cost	BRL GJ^{-1}	13.85	13.85	13.85
	Inefficiency Cost	BRL h^{-1}	10,725.72	8,304.78	8,304.78
Turbine	Destroyed Exergy	GJ/h	0.85	3.92	3.92
	Fuel Cost	BRL GJ^{-1}	29.74	17.41	16.75
	Inefficiency Cost	BRL h^{-1}	25.28	68.24	65.66
Pressure-Reducing Valve	Destroyed Exergy	GJ/h	50.62	0.38	0.38
	Fuel Cost	BRL GJ^{-1}	29.74	17.41	16.75
	Inefficiency Cost	BRL h^{-1}	1,505.23	6.62	6.37
TOTAL	—	BRL h^{-1}	12,256.23	8,379.64	8,376.81

The monetary impact of unutilized steam at Point 8 is illustrated in Figure 6. A compelling insight emerges from the comparison between Case 1 and Case 2: although the physical exergy loss slightly increases in Case 2 (from 39.8 to 41.0 GJ h^{-1}), the associated hourly cost decreases by more than 55% (from approximately 1,668 to 738 BRL h^{-1}). This apparent paradox is inherent to the exergoeconomic framework; the overall efficiency gains achieved in Case 2 significantly reduce the unit cost of low-pressure steam (c_6), so that a comparable amount of discarded energy carries a substantially lower economic burden for the plant.

Case 3 represents the optimal configuration, in which the hourly loss cost is minimized to only 138.22 BRL h^{-1}. This result is achieved through a dual mechanism: a drastic reduction in the volume of surplus steam (to 7.5 GJ h^{-1}) combined with the lowest specific steam cost among all scenarios. When these findings are interpreted in conjunction with the inefficiency costs reported in Table 17, it becomes evident that redirecting steam previously dissipated in the pressure-reducing valve toward productive expansion in the turbine not only reduces internal exergy destruction but also virtually eliminates the external economic penalty associated with wasted energy. These results confirm that the Flex 360 configuration is the most effective strategy for mitigating the financial risks of energy underutilization in flexible biorefineries.

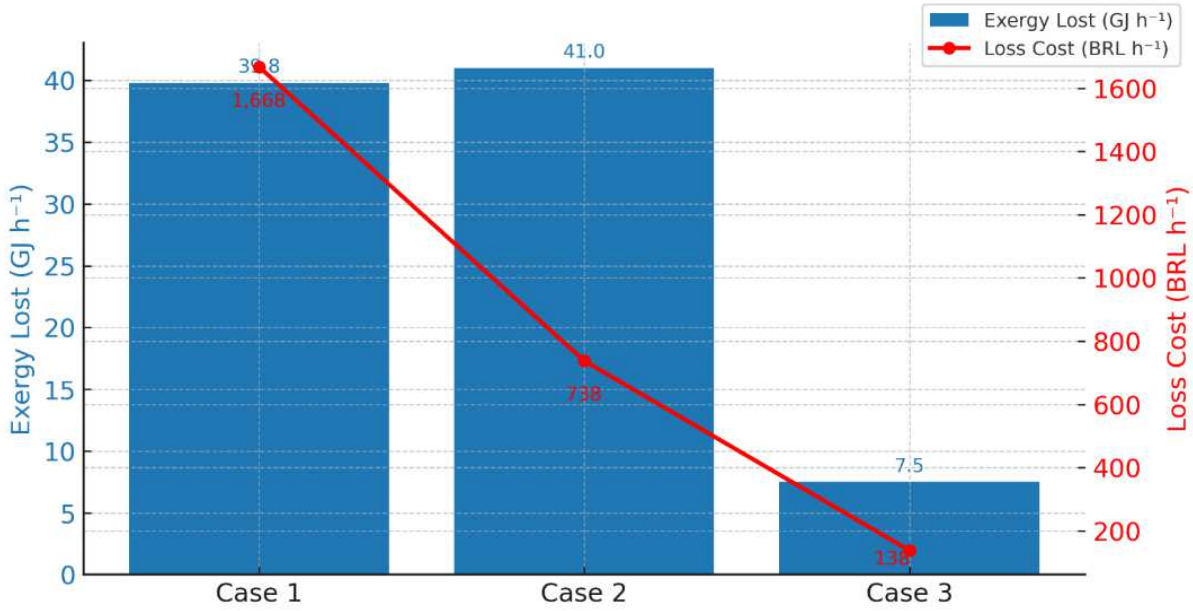


Figure 6 Hourly Cost of Exergy Losses by Scenario

Overall, the exergoeconomic analysis confirms that shifting the plant's strategy from a seasonal to an integrated configuration (Case 3) delivers simultaneous gains in thermodynamic efficiency and cost reduction. By reducing internal exergy destruction in the boiler and pressure-reducing valves, while virtually eliminating external steam venting losses, the Flex 360 configuration emerges as the most energy-efficient and economically attractive pathway for the evaluated biorefinery.

Most previous studies assess thermodynamic performance under steady-state or harvest-period conditions, whereas the present work provides an annualized evaluation incorporating seasonal transitions. For this reason, direct numerical comparisons should be interpreted cautiously. Nevertheless, the annual exergy efficiency achieved in the Flex 360 configuration remains within the upper range reported for advanced integrated ethanol systems [8,9], while offering a more comprehensive techno-economic perspective.

4.3. Sensitivity Analysis

A first-order sensitivity analysis was performed to evaluate the influence of key economic parameters on the formation of product and utility costs in the proposed biorefinery configurations. The analysis considered variations of −40%, −20%, +20%, and +40% in the prices of sugarcane, corn, and sugarcane bagasse, while the competitiveness of surplus electricity was assessed against representative electricity market values.

The updated production costs were estimated from the baseline exergoeconomic results using a first-order parametric approach. In this formulation, the sensitivity coefficient (α) was defined as the ratio between the exergy-based unit cost of the corresponding feedstock and the baseline exergoeconomic unit cost of the product or utility. This definition is consistent with the cost allocation principles of the SPECO methodology, in which variations in resource costs propagate through the cost balance structure of the system [25].

This approach provides a physically consistent representation of how economic fluctuations affect the thermoeconomic performance of the plant, preserving the interactions between process units and cost formation mechanisms. Similar parametric and sensitivity-based analyses have been widely applied in thermoeconomic evaluations of energy systems and biorefineries, providing reliable insights into the impact of market uncertainties on production costs [8,39,43].

4.3.1. Impact of Feedstock Prices on Ethanol Cost

The results indicate that sugarcane ethanol costs are moderately sensitive to feedstock price variations, whereas corn ethanol exhibits a significantly stronger response (Tables 18 and 19).

Table 18 Sensitivity of sugarcane ethanol cost (BRL L^{-1}) to variations in sugarcane price.

Sugarcane Price Variation	Case 1	Case 2	Case 3
- 40 %	1.63	1.21	1.15
- 20 %	1.76	1.34	1.28
Baseline (0%)	1.90	1.48	1.42
+ 20 %	2.04	1.62	1.56
+ 40 %	2.17	1.75	1.69

Table 19 Sensitivity of corn ethanol cost (BRL L^{-1}) to variations in corn price.

Corn Price Variation	Case 1	Case 2	Case 3
- 40 %	—	0.81	0.80
- 20 %	—	1.10	1.09
Baseline (0%)	—	1.40	1.39
+ 20 %	—	1.70	1.69
+ 40 %	—	1.99	1.98

The results presented in Tables 18 and 19 are further illustrated in Figures 7 and 8.

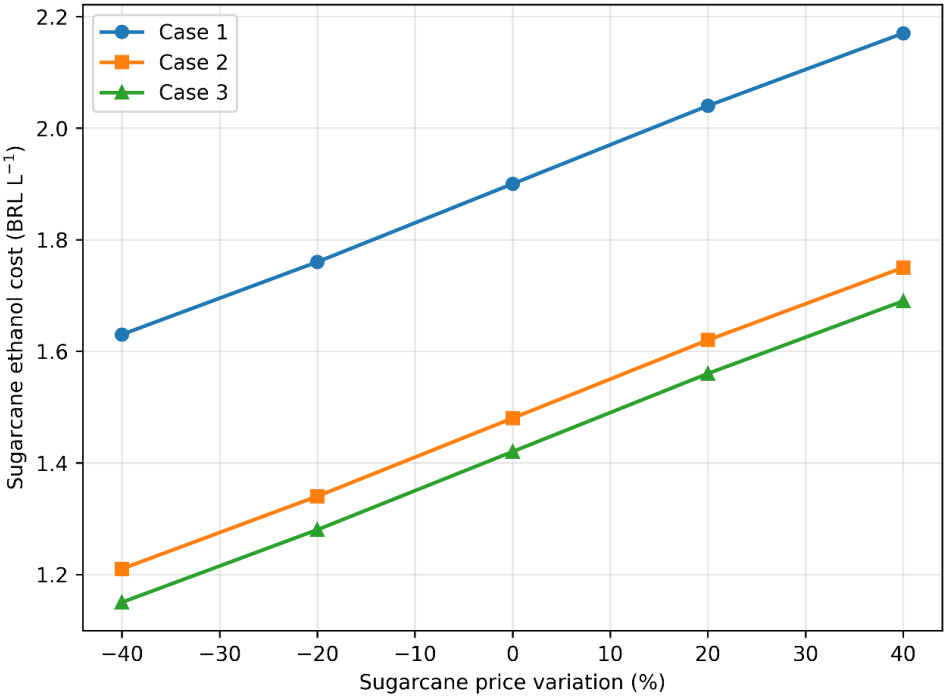


Figure 7 Sensitivity of sugarcane ethanol cost to sugarcane price variations.

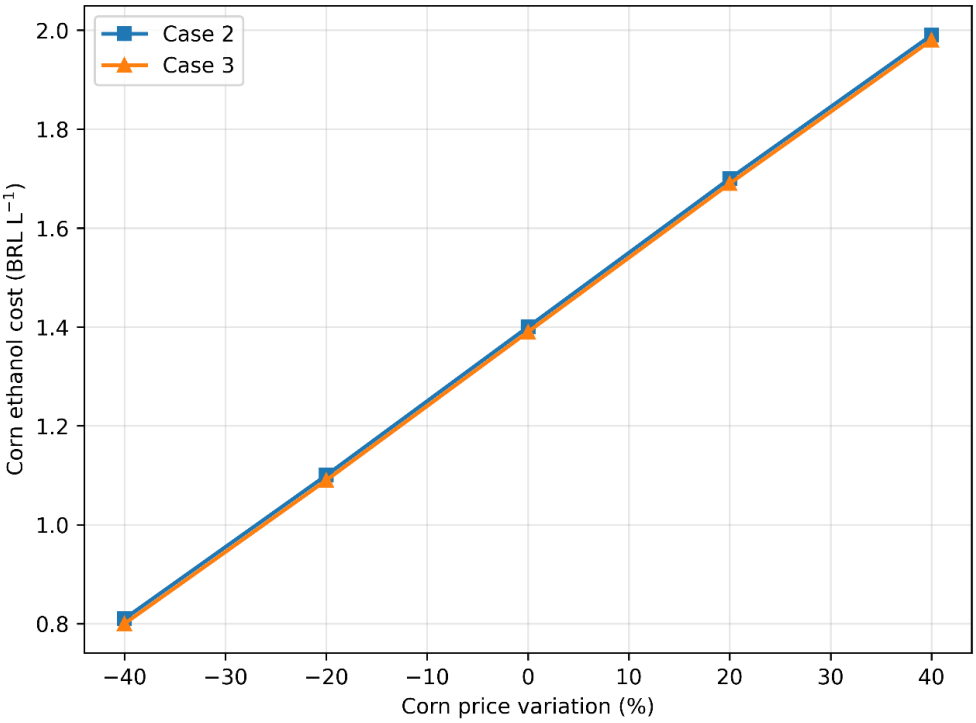


Figure 8 Sensitivity of corn ethanol cost to corn price variations.

As shown in Figures 7 and 8, corn ethanol exhibits a significantly steeper cost variation compared to sugarcane ethanol, indicating a higher sensitivity to feedstock price fluctuations. Notably, the sensitivity coefficient for corn ethanol exceeds 1.0 (approximately 1.06 in Case 3). This amplified response can be attributed to the cost allocation structure adopted in the SPECO methodology, in which high-value coproducts (DDGS and corn oil) are treated as external market-valued streams.

As a result, variations in corn feedstock price are predominantly absorbed by the ethanol stream, which acts as the main cost carrier within the system. This behavior highlights the sensitivity of the corn ethanol pathway to feedstock price volatility, while also indicating that favorable market conditions can significantly enhance its economic performance, leading to production costs approaching 0.80 BRL L^{-1} under favorable conditions.

In contrast, sugarcane ethanol presents a more moderate slope, as observed in Figure 7, indicating greater stability under varying economic conditions. Furthermore, Figures 7 and 8 demonstrate that the fully integrated configuration (Case 3) consistently achieves the lowest production costs across all scenarios for both ethanol pathways.

4.3.2. Impact of Bagasse Price on Internal Utilities

The cost of internal steam utilities showed significant sensitivity to bagasse pricing, reflecting its role as the primary fuel for the cogeneration system (Tables 20 and 21).

Table 20 Sensitivity of high-pressure steam cost (Point 1, BRL GJ^{-1}) to variations in bagasse price.

Bagasse Price Variation	Case 1	Case 2	Case 3
- 40 %	24.20	11.87	11.21
- 20 %	26.97	14.64	13.98
Baseline (0%)	29.74	17.41	16.75

+ 20 %	32.51	20.18	19.52
+ 40 %	35.28	22.95	22.29

Table 21 Sensitivity of low-pressure process steam cost (Point 6, BRL GJ^{-1}) to variations in bagasse price.

Bagasse Price Variation	Case 1	Case 2	Case 3
- 40 %	36.36	12.46	12.89
- 20 %	39.13	15.23	15.66
Baseline (0%)	41.90	18.00	18.43
+ 20 %	44.67	20.77	21.20
+ 40 %	47.44	23.54	23.97

The results presented in Tables 20 and 21 are further illustrated in Figure 9.

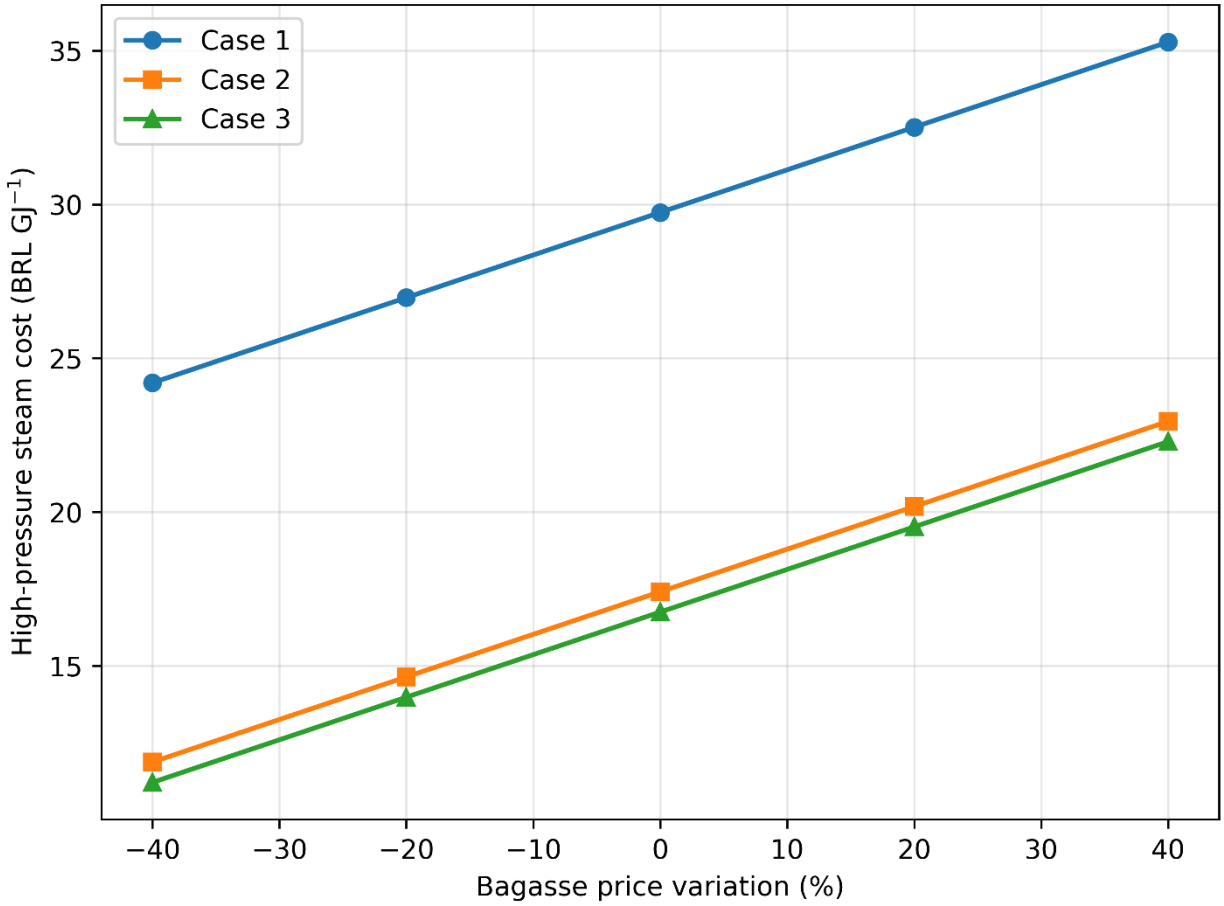


Figure 9 Sensitivity of high-pressure steam cost (Point 1) to bagasse price variations.

The analysis confirms the economic advantage of the integrated configurations. As illustrated in Figure 9, even under a scenario where the bagasse price increases by 40%, the cost of high-pressure steam in Case 3 (22.29 BRL GJ^{-1}) remains substantially lower than the baseline cost observed in Case 1 (29.74 BRL GJ^{-1}), reflecting the superior thermodynamic efficiency and resource

utilization of the integrated system. This result highlights that improvements in continuous operation and asset utilization outweigh moderate increases in fuel costs.

4.3.3. Economic Competitiveness of Surplus Electricity

Finally, the economic competitiveness of surplus electricity was evaluated by calculating the unit margin (market price minus exergoeconomic production cost) across different electricity market scenarios. Since Case 1 does not generate surplus power, the analysis focuses on Cases 2 and 3 (Table 22).

Table 22 Economic margin of surplus electricity (BRL MWh^{-1}) under varying market prices.

Market Price Scenario (BRL MWh^{-1})	Case 1 Margin	Case 2 Margin	Case 3 Margin
58.60 (Regulatory PLD Floor)	—	- 4.09	- 1.71
100.00	—	37.31	39.69
150.00	—	87.31	89.69
200.00	—	137.31	139.69
300.00 (Typical Free Market - ACL)	—	237.31	239.69

The results presented in Table 22 are further illustrated in Figure 10.

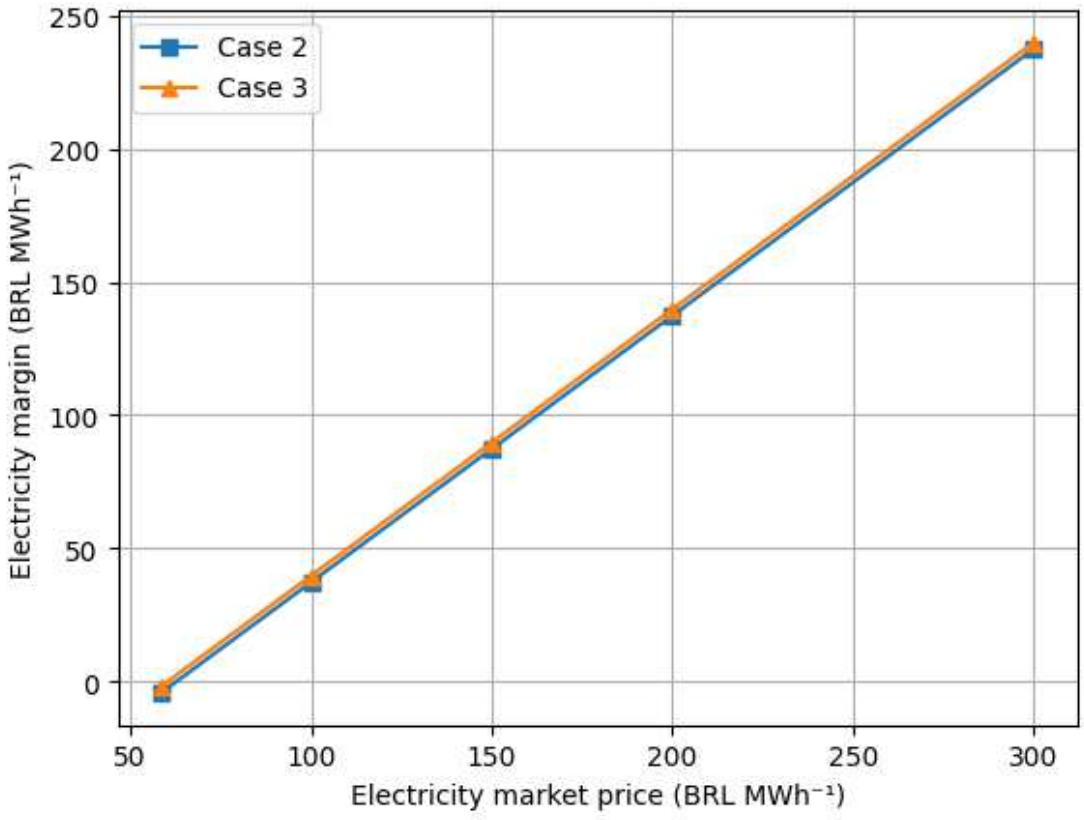


Figure 10 Economic margin of surplus electricity under different market price scenarios.

As illustrated in Figure 10, under the lower-bound reference of the spot market price (PLD = 58.60 BRL MWh^{-1}), the integrated configurations operate close to break-even conditions, with minor deficits. However, under typical Free Contracting Market (ACL) conditions, where forward contracts frequently reach or exceed 300.00 BRL MWh^{-1}, both configurations provide substantial profit margins, reaching up to 239.69 BRL MWh^{-1} in Case 3.

Overall, the sensitivity analysis demonstrates that the Flex 360 configuration (Case 3) represents the most thermodynamically efficient and economically robust operating strategy, maintaining lower baseline costs and greater resilience under a broad range of economic conditions.

5. Conclusions

This study demonstrates that the transition from a conventional sugarcane-based plant to a fully integrated sugarcane–corn flexible biorefinery fundamentally reshapes both thermodynamic performance and cost formation. Among the evaluated configurations, the fully integrated year-round operation (Case 3) clearly emerges as the technically and economically superior option, confirming that maximum feedstock diversification combined with continuous operation is the most effective strategy for modern bioenergy systems.

From a thermodynamic perspective, the transition from Case 1 to Case 3 represents a substantial efficiency leap, with the overall annual yield increasing from 25.27% to 61.26%. This improvement is primarily driven by the integration of corn ethanol production, which establishes a continuous thermal demand and drastically reduces unutilized steam—from 64.9 t h^{-1} to 9.1 t h^{-1} during the harvest season—while simultaneously enabling more robust cogeneration during the off-season.

The exergoeconomic assessment translates these performance gains into clear financial benefits by explicitly monetizing thermodynamic irreversibilities. The reconfiguration of steam flows emerges as the most impactful intervention, virtually eliminating the inefficiency cost associated with the pressure-reducing valve, which drops from 1,505.44 BRL h^{-1} in the baseline scenario to only 6.37–6.62 BRL h^{-1} in the integrated cases. This change propagates through the internal utility network, reducing the unit cost of high-pressure steam by approximately 44% (from 29.74 to 16.75 BRL GJ^{-1}), lowering low-pressure process steam costs from 41.90 to 18.00–18.43 BRL GJ^{-1}, and decreasing pressurized feedwater costs from 23.42 to 18.05–18.65 BRL GJ^{-1}.

As a direct consequence, the fully integrated configuration achieves the most favorable economic performance, with sugarcane ethanol produced at 1.42 BRL L^{-1} and surplus electricity at 60.31 BRL MWh^{-1}. The corn ethanol route remains equally competitive (1.39–1.40 BRL L^{-1}), while revenues from DDGS and crude corn oil further enhance the economic robustness of the system.

In addition, the sensitivity analysis confirms that the integrated configuration is not only more efficient but also more resilient to market fluctuations. Even under significant variations in feedstock and energy prices, Case 3 maintains lower production costs and superior economic margins, demonstrating its robustness under realistic operating conditions.

Overall, this work provides quantitative evidence that integrating feedstocks and optimizing cogeneration at the system level is a decisive pathway to enhance efficiency, profitability, and economic resilience in flex biorefineries. By linking exergy destruction directly to monetary penalties, the exergoeconomic framework proves to be a powerful decision-support tool, capable of identifying and prioritizing interventions that maximize exergy utilization and guide the strategic evolution of the Brazilian bioenergy sector.

The proposed approach fulfills the research objectives by systematically quantifying exergy-based cost formation under alternative operational strategies and identifying the main thermoeconomic drivers of system performance. From an industrial

perspective, the findings suggest that strategic investments in continuous operation and steam network optimization may yield greater economic benefits than isolated equipment-level improvements.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT to assist with language clarity and organization. After using this tool, the authors reviewed and edited the content as needed, and take full responsibility for the content of this publication.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability

Data will be made available upon reasonable request.

Bibliographic References

[1] Companhia Nacional de Abastecimento (CONAB). *Acompanhamento da safra brasileira de cana-de-açúcar*. v. 11 – Safra 2024/25, n. 3 – Terceiro levantamento. Brasília; 2024.

[2] Dias MOS, Junqueira TL, Cavalett O, Jesus CDF, Rossell CEV, Maciel Filho R, Bonomi A. Integrated versus stand-alone second generation ethanol production from sugarcane bagasse and trash. **Bioresour Technol**. 2012;103(1):152–161. https://doi.org/10.1016/j.biortech.2011.09.120

[3] Silva APM, et al. Integration of corn and cane for ethanol production. **Fermentation**. 2023;9(2):89. https://doi.org/10.3390/fermentation9020089

[4] Pérez-Almada D, Galán-Martín Á, Contreras MDM, Castro E. Integrated techno-economic and environmental assessment of biorefineries: Review and future research directions. **Sustain Energy Fuels**. 2023;7:4021–4042. https://doi.org/10.1039/D3SE00405H

[5] Bejan A, Tsatsaronis G, Moran MJ. *Thermal design and optimization*. New York: Wiley; 1996.

[6] Valero A, Lozano MA, Muñoz M. A general theory of exergy saving. **Energy**. 1994;19(3):279–286.

[7] Ensinas AV. *Integration of thermal processes in biorefineries: The case of the Brazilian sugar and ethanol industry* [PhD thesis]. Zaragoza: University of Zaragoza; 2008.

[8] Pellegrini LF, de Oliveira Junior S. Exergoeconomic analysis of a sugarcane mill with compressed air energy storage. **Appl Therm Eng**. 2011;31(10):1676–1686.

[9] Junqueira TL, Chagas MF, Gouveia VL, Watanabe MD, Bonomi A. Techno-economic and environmental assessment of second generation ethanol: Short- and long-term prospects. **Biotechnol Biofuels**. 2017;10:44. https://doi.org/10.1186/s13068-017-0722-3

[10] Donke ACG. *Technical-economic study of ethanol production from corn in Brazil* [MSc thesis]. São Paulo: University of São Paulo; 2016.

[11] Neves MF, Trombin VG, Consoli MA. *Corn ethanol in Brazil*. São Paulo: SNA; 2021.

[12] Oliveira LSBL, Cruz AJG. Techno-economic analysis and carbon intensity of sugarcane–corn flex plants in Brazil. **Bioresour Technol Rep**. 2023;24:101694. https://doi.org/10.1016/j.biteb.2023.101694

[13] Sumikawa D, Silva Neto AJP, Ribeiro BDL, Maciel Filho R, Wolf Maciel MR. Technoeconomic evaluation of a flex ethanol plant of sugarcane and corn in Brazil. **Chem Eng Technol**. 2022;45(1):78–90. https://doi.org/10.1002/ceat.202100177

[14] Pellegrini LF, de Oliveira Junior S. Combined production of sugar, ethanol and electricity: Thermoeconomic and environmental analysis and optimization. **Energy**. 2011;36(6):3704–3715.

[15] SimTech Simulation Technology. *IPSEpro – Integrated Process Simulation Environment* [software]. Graz; 2024.

[16] Klein SA, Alvarado FL. *EES – Engineering Equation Solver*, Version 11.624 [software]. Middleton (WI): F-Chart Software; 2024.

[17] Bejan A. *Advanced engineering thermodynamics*. Hoboken: Wiley; 2016.

[18] Moran MJ, Shapiro HN, Boettner DD, Bailey MB. *Fundamentals of engineering thermodynamics*. Hoboken: Wiley; 2014.

[19] Kotas TJ. *The exergy method of thermal plant analysis*. Oxford: Butterworth-Heinemann; 1995.

[20] Himmelblau DM, Bischoff KB. *Process analysis and simulation: Deterministic systems*. New York: Wiley; 2003.

[21] Çengel YA, Boles MA. *Thermodynamics: An engineering approach*. 8th ed. New York: McGraw-Hill; 2014.

[22] Dincer I, Rosen MA. *Exergy: Energy, environment and sustainable development*. Oxford: Elsevier; 2012.

[23] Sciubba E, Wall G. Exergy, energy system analysis and optimization. In: **Encyclopedia of Life Support Systems (EOLSS)**. Oxford: UNESCO; 2007.

[24] Lora EES, Palacio JCE, Rocha MH. *Termodinâmica*. Florianópolis: UFSC; 2008.

[25] Lazzaretto A, Tsatsaronis G. SPECO: A systematic and general methodology for calculating efficiencies and costs in thermal systems. **Energy**. 2006;31(8–9):1257–1289.

[26] Szargut J, Morris DR, Steward FR. *Exergy analysis of thermal, chemical and metallurgical processes*. Washington (DC): Hemisphere; 1988.

[27] Van Gool W. The value of exergy. In: *Proceedings of the 5th International Conference on Energy for a Sustainable World*. London: Elsevier Applied Science; 1990. p. 23–36.

[28] Bridgwater AV. Renewable fuels and chemicals by thermal processing of biomass. **Chem Eng J**. 2003;91(2–3):87–102.

[29] Van Loo S, Koppejan J. *The handbook of biomass combustion and co-firing*. London: Earthscan; 2008.

[30] Saidur R, Abdelaziz EA, Demirbas A, Hossain MS, Mekhilef S. A review on biomass as a fuel for boilers. **Renew Sustain Energy Rev**. 2011;15(5):2262–2289.

[31] Boyle G. *Renewable energy: Power for a sustainable future*. 3rd ed. Oxford: Oxford University Press; 2012.

[32] Horlock JH. *Cogeneration: Combined heat and power*. Oxford: Pergamon; 1987.

[33] Kehlhofer R, Bachmann R, Nielsen H, Warner J. *Combined-cycle gas and steam turbine power plants*. Tulsa: PennWell; 1999.

[34] Lima RNO, Fernandes PC. Efficiency indicators in cogeneration schemes. **Cienc Eng (Uberlandia)**. 2006;15(1–2):79–81.

[35] Seabra JEA, Macedo IC, Chum HL, Faroni CE, Sarto CA. Life cycle assessment of Brazilian sugarcane products: GHG emissions and energy use. **Biofuels Bioprod Bioref**. 2011;5(5):519–532.

[36] Pellegrini LF, de Oliveira Jr S. Exergy analysis of sugarcane bagasse gasification. **Energy**. 2007;32(4):314–327.

[37] Morosuk T, Tsatsaronis G. Advanced exergy-based methods used to understand and improve energy-conversion systems. **Energy**. 2019;169:238–246.

[38] Bonforte G, Buchgeister J, Manfrida G, Petela K. Exergoeconomic and exergoenvironmental analysis of an integrated solar gas turbine/combined cycle power plant. **Energy**. 2018;156:352–359.

[39] Soltanian S, Aghbashlo M, Farzad S, Tabatabaei M, Mandegari M, Görgens JF. Exergoeconomic analysis of lactic acid and power cogeneration from sugarcane residues through a biorefinery approach. **Renew Energy**. 2019;143:872–889.

[40] Anvari S, Khalilarya S, Zare V. Exergoeconomic and environmental analysis of a novel configuration of solar-biomass hybrid power generation system. **Energy**. 2018;165:776–789.

[41] Tsatsaronis G, Winhold M. Exergoeconomic analysis and evaluation of energy-conversion plants—I: A new general methodology. **Energy**. 1985;10(1):69–80.

[42] Dias MOS, Modesto M, Ensinas AV, Nebra SA, Maciel Filho R, Rossell CEV. Improving bioethanol production from sugarcane: Evaluation of distillation, thermal integration and cogeneration systems. **Energy**. 2011;36(6):3691–3703.

[43] Kumar R. A critical review on energy, exergy, exergoeconomic and economic (4-E) analysis of thermal power plants. **Eng Sci Technol Int J**. 2017;20(1):283–292.

[44] Rocha G. *Análise termodinâmica, termoeconômica e econômica de uma usina sucroalcooleira com processo de extração por difusão* [MSc dissertation]. UNESP; 2010.

[45] Effatpanah SK, Ahmadi MH, Delbari SH, Lorenzini G. Energy, exergy, exergoeconomic and emergy-based exergoeconomic analyses of a biomass combustion waste heat recovery ORC. **Entropy**. 2022;24:209.

[46] Cherubini F. The biorefinery concept: Using biomass instead of oil for producing energy and chemicals. **Energy Convers Manag**. 2010;51(7):1412–1421. https://doi.org/10.1016/j.enconman.2010.01.015

[47] MF Rural. Bagaço de cana – anúncios de compra e venda no Brasil [Internet] [in Portuguese]. 2025 [cited 2026 Feb 6]. Available from: https://www.mfrural.com.br/busca/venda-bagaco

[48] NovaCana. Bagaço da cana pode ganhar o mundo e criar novo mercado para usinas [Internet] [in Portuguese]. 2016 Mar 11 [cited 2026 Feb 6]. Available from: https://www.novacana.com/noticias/bagaco-cana-ganhar-mundo-novo-mercado-usinas-110316

[49] Notícias Agrícolas. Cana básica – PR (Consecana-PR quotation) [Internet] [in Portuguese]. [cited 2026 Feb 10]. Available from: https://www.noticiasagricolas.com.br/cotacoes/sucroenergetico/acucar-preco-da-cana-basica-pr

[50] CEPEA – Centro de Estudos Avançados em Economia Aplicada. Indicador do milho ESALQ/B3 [Internet] [in Portuguese]. 2025 [cited 2026 Feb 6]. Available from: https://www.cepea.org.br/br/indicador/milho.aspx

[51] ABISA. Corn oil quotations – Editora Stilo [Internet]. 2025.

[52] Corassa A, Lautert IPAS, Pina DS, Kiefer C, Ton APS, Komiyama CM, et al. Nutritional value of Brazilian DDGS for pigs. **Rev Bras Zootec**. 2017;46(9):740–746.

[53] Patzek TW. Thermodynamics of the corn-ethanol biofuel cycle. **Crit Rev Plant Sci**. 2004;23(6):519–567.

[54] Demirbas A. Fuel properties and calculation of higher heating values of vegetable oils. **Fuel**. 1998;77(9–10):1117–1120.

[55] ANEEL – Agência Nacional de Energia Elétrica. Aneel define tarifas de energia de otimização de serviços ancilares e PLD para 2025 [Internet] [in Portuguese]. Brasília: ANEEL; 2024 [cited 2026 Feb 6]. Available from: https://www.gov.br/aneel/pt-br/assuntos/noticias/2024/aneel-define-tarifas-de-energia-de-otimizacao-de-servicos-ancilares-e-pld-para-2025

[56] MegaWhat. Preços em contratos de curto a médio prazo ultrapassam R$ 300/MWh [Internet] [in Portuguese]. 2025 Mar 19

[cited 2026 Feb 6]. Available from: http://megawhat.uol.com.br/mercado-livre/precos-em-contratos-de-curto-a-medio-prazo-ultrapassam-r-300-mwh/