

Article

The Sustainability of Biomass as a Fuel in the Sugar Industry: A Generalizable Protocol for Energy, Exergy, and Emergy to Assess Quantity, Quality, and Environmental Cost

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Abstract

The sustainability of biomass utilization as a fuel is commonly assessed through thermodynamic and ecological methods—energy, exergy, and emergy analyses—applied in isolation, each with only partial scope. Their integration through multicriteria analysis has been proposed for the sugar industry, but has not yet been formalized as a reproducible, auditable, and generalizable protocol: neither the logical sequence linking balances and decision-making, nor an explicit sustainability rule, nor the treatment of the incommensurability between thermodynamic and ecological accounting has been established. This work formalizes such a protocol in three stages: (i) definition of fuel alternatives and screening of criteria through the Delphi method; (ii) characterization of each alternative through three coupled balances—energy (quantity), exergy (quality), and emergy (environmental cost); and (iii) integration through the Analytic Hierarchy Process (AHP) into a single sustainability ranking with an explicit decision rule, supported by a robustness layer based on Monte Carlo simulation and multi-method comparison. The protocol is demonstrated in the Cuban sugar industry using two steam generators (G.V. VU-40 and Retal-type steam generator) and variants of bagasse, agricultural harvest residues (AHR), and marabou (*Dichrostachys cinerea*). In the demonstration, AHP weighting ranked the emergy criterion above the exergy and energy criteria (priority vectors 0.539, 0.297, and 0.164, respectively; consistency ratio 0.008), and the bagasse alternative emerged as the most sustainable in both technologies despite not being the most efficient. The robustness analysis confirmed that this verdict is stable: bagasse Pareto-dominates the independent emergy indicators and remains the best alternative in more than 95% of the weight space. The contribution of the work is methodological—the formalization and generalization of the protocol—while the case study illustrates its operation and does not constitute a statistical validation.



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Keywords: energy analysis; exergy analysis; emergy synthesis; multi-criteria decision-making; analytic hierarchy process; sustainability assessment; biomass fuels; sugar industry; transformity; *Dichrostachys cinerea*

1. Introduction

The sugar industry is one of the largest agro-industrial systems on the planet: approximately 115 countries annually produce nearly 1.9 billion tonnes of sugarcane, making it the world's largest crop by production volume, led by Brazil, India, China, Thailand, and Australia [1,2]. Each tonne of sugarcane generates a considerable amount of residual biomass—bagasse and agricultural harvest residues (AHR)—available within the process itself, enabling sugar mills to self-supply steam and electricity through cogeneration and, increasingly, to export surplus electricity to the grid [1]. This resource gives the sugar industry a singular role in the energy transition: globally, sugarcane biomass from the eight largest producers represents an electricity generation potential on the order of 40 GW [2].

In Cuba, where steam generators of different technologies coexist and where marabou (*Dichrostachys cinerea*)—an invasive woody species with high potential as a complementary fuel—is also available, deciding which fuel or fuel mixture to utilize, in which technology, and under which sustainability criterion constitutes a non-trivial decision problem; moreover, it is a problem of general relevance for all sugar-producing countries.

A distinctive feature of sustainability assessment in power plants is that it cannot rely on a single analysis: it requires both thermodynamic and environmental parameters [3]. These are expressed through three complementary lenses. Energy analysis, grounded in the first law of thermodynamics, quantifies *how much* energy is utilized. *Exergy analysis*, based on the second law, measures the *quality* or useful work potential available and identifies the system's irreversibilities [4–7]. *Emergy synthesis*, rooted in systems ecology [8–10], accounts for the *environmental cost*, that is, the equivalent solar energy that nature and the economy have invested to make the resource available.

Each method contributes an indispensable component to sustainability assessment but, when applied in isolation, provides only a partial perspective: the option with the highest first-law efficiency is not necessarily the one with the highest thermodynamic quality nor the one with the lowest environmental burden.

The literature has extensively developed these perspectives, but in a fragmented manner. Exergy analysis of steam generators and power cycles is a mature practice: numerous studies have identified the boiler as the component with the highest exergy destruction in the cycle and have quantified the contrast between first- and second-law efficiencies [11–14]. Applied specifically to bagasse-based cogeneration, this approach has a long trajectory ranging from pioneering studies on sugar plants [15,16] to recent assessments incorporating economic and environmental criteria [3,17], increasingly supported by process simulation [18]. In parallel, life cycle assessment and thermoeconomic analysis of the combined production of sugar, ethanol, and electricity have been applied in the major producing countries [19–23], in line with the growing adoption of LCA as a standard tool for evaluating bioenergy sustainability [24,25]. Emergy synthesis, in turn, has demonstrated its usefulness for comparing electricity and bioenergy production systems in terms of renewability and environmental burden [26–28]; however, its application to the sugar industry has been limited and has focused mainly on ethanol production, rarely addressing the combustion of biomasses other than bagasse or fuel blends. More recently, integrated “4E” frameworks that jointly consider energy, exergy, economic, and emergy accounting have been proposed for biomass-based and multigeneration energy systems, confirming a growing convergence toward multi-lens sustainability assessment in which the emergy sustainability index plays a decisive role in the final decision [29,30].

To support decision-making among energy alternatives when multiple conflicting criteria coexist, multicriteria decision-making (MCDM) methods have become the reference tool [31–33]. The analytic hierarchy process (AHP) [34–36], the TOPSIS method [37], and PROMETHEE [38] have been extensively employed—often in fuzzy or hybrid variants—

to select renewable energy technologies and sources across numerous countries and contexts [39–47], as well as in the sustainability assessment of projects and processes in general [48–50]. The selection and screening of criteria are commonly supported by the Delphi method [51,52], whose degree of expert consensus is quantified through Kendall's coefficient of concordance [53]. Nevertheless, in practice these methods are usually applied to criteria defined within a single analytical framework, without systematically coupling the three thermodynamic–ecological lenses.

The simultaneous integration of the energetic, exergetic, and emergy methods to evaluate the sustainability of biomasses and their blends as fuels in the sugar industry has only very recently been proposed, through the Delphi–AHP combination [54] and the AHP–TOPSIS combination [55]. These contributions establish a *decision-making method* for a specific case, but they do not constitute a reproducible, auditable, and generalizable *protocol*. In particular, the following aspects have not been explicitly established: (i) the logical sequence linking the computation of balances with criteria screening and ranking—so that the indicators constituting the criteria are calculated before being weighted—; (ii) the decision rule determining when an alternative is sustainable and, otherwise, triggering the revision of the fuel blend; (iii) the treatment of the incommensurability between thermodynamic accounting (energy and exergy, partially correlated) and ecological accounting (emergy); nor (iv) a robustness layer verifying the stability of the ranking against uncertainty in expert judgments. This gap—the absence of a formal procedure leading from the three balances to a robust and reproducible sustainability decision—is what this work addresses.

To fill this gap, a biomass fuel sustainability assessment protocol is formalized, operating in three stages: *Stage 1*, definition of fuel alternatives and their blends, together with the screening of criteria and subcriteria through the Delphi method; *Stage 2*, characterization of each alternative through three coupled balances—energetic (quantity), exergetic (quality), and emergy-based (environmental cost)—from which the indicators acting as criteria are derived; and *Stage 3*, integration of these indicators through AHP into a single sustainability ranking, governed by an explicit decision rule and supported by a robustness layer. The novelty lies in the *formalization* of the protocol—its sequence, its decision rule, and its uncertainty layer—and in its conception as a *generalizable* procedure: although demonstrated in the Cuban sugar industry, its logic is transferable to any sugar mill worldwide—a sector present in more than one hundred countries [1]—and, more broadly, to any sector required to select biomass fuels while simultaneously considering the quantity, quality, and environmental cost of energy. The contribution is therefore methodological rather than the derivation of a numerical result for a particular case.

The protocol is demonstrated in the Cuban sugar industry, using two steam-generation technologies currently operating in the country—the high-pressure G.V. VU-40 steam generator and the Retal-type steam generator—and fuel variants constructed from bagasse, AHR, *Dichrostachys cinerea*, and their blends. It is emphasized that the study is presented as a *single-case demonstration*, not as a typological validation: the contribution is methodological—the formalization of the transition from balances to decision-making—and the case serves to illustrate the operation and plausibility of the protocol rather than to establish statistical generalization. Consequently, the numerical results of the case are presented as an illustration supported by the sources reporting them in detail.

Consistent with the above, the general objective of this work is to *formulate and demonstrate a generalizable protocol, based on the integration of energetic, exergetic, and emergy analyses through multicriteria decision-making, for the sustainability assessment of biomasses as fuels*.

The remainder of the paper is organized as follows. Section 2 describes the case study and formalizes the three-stage protocol: definition of alternatives and Delphi screening, coupled energetic–exergetic–emergy balances, AHP integration with its decision rule, and the

robustness layer. Section 3 applies the protocol to the sugar-industry case and reports the indicators derived from each balance, the multicriteria ranking, and the robustness analysis. Section 4 interprets the findings, positions the protocol within the literature, and delimits its scope. Finally, Section 5 synthesizes the results, the methodological contribution, and future research directions.

2. Materials and Methods

Throughout this section, a distinction is maintained between the *invariant elements of the protocol* and the *case-specific instantiation* adopted for the demonstration. The invariant elements—the three-stage sequence, the three coupled balances, the explicit decision rule, and the robustness layer—constitute the transferable methodological contribution and remain unchanged in any application. The specific fuels, steam-generator technologies, expert panel, and criteria weights are instances that may be redefined for a different sector or feedstock. Table 1 makes this correspondence explicit, so that the reader can identify at once which components are fixed and which are particular to the Cuban sugar-industry case.

Table 1. Correspondence between the invariant elements of the protocol and their instantiation in the Cuban sugar-industry demonstration.

Protocol Element (Invariant)	Case-Study Instantiation (Specific)
Stage 1—Definition of alternatives	Five fuel variants (V1–V5) from bagasse, AHR, and <i>D. cinerea</i>
Stage 1—Criteria screening (Delphi)	Panel of 15 experts; 12 sub-criteria retained; $W = 0.796$
Stage 2—Energy balance	Direct/indirect method + Aspen Plus, two steam generators
Stage 2—Exergy balance	Control-volume exergy balance on both generators
Stage 2—Emergy synthesis	%R, EYR, ELR, ESI; transformity of <i>D. cinerea</i> determined
Stage 3—AHP integration & decision rule	Weights (0.164, 0.297, 0.539); rule: $\max P_a$ s.t. $ESI \geq 1$
Robustness layer	Dirichlet Monte Carlo ($N = 10,000, \kappa = 50$), Pareto, TOPSIS/PROMETHEE

2.1. Case Study and Data

The protocol is demonstrated on two steam generators representative of the Cuban sugar industry: the high-pressure G.V. VU-40 and the Retal-type steam generator. For each technology, fuel variants constructed from three biomasses—sugarcane bagasse, AHR, and *Dichrostachys cinerea*—and their blends are evaluated, as defined in Table 2. The characterization of each fuel (lower heating value, proximate and ultimate composition, availability) and the technical operating data of both technologies are taken from the sources reporting them in detail [18,54] and are summarized in the Supplementary Material.

The two technologies differ primarily in their operating steam pressure and, consequently, in their thermodynamic performance envelope. The Retal-type generator—the most widely installed technology in Cuban sugar mills, available in 45 t/h and 60 t/h configurations—operates at a steam pressure of 1.9 MPa and 320 °C, with a feedwater temperature of 80 °C and flue-gas outlet temperature of 213.7 °C. The G.V. VU-40, a higher-parameter technology recently installed in a bioelectric plant, operates at a design pressure of 8.0 MPa (6.2 MPa in operation) and 450 °C, with a nominal capacity of 235 t/h and a feedwater temperature of 137 °C. This higher operating pressure is the physical reason why the VU-40 consistently outperforms the Retal unit by approximately 5% in energy efficiency across all variants. Other steam-generation technologies exist in the Cuban sugar industry; these two were selected as representative of two contrasting pressure levels, which allows the sensitivity of the protocol to the technology to be illustrated without enlarging the demonstration case. The complete operating parameters of both units are provided in the Supplementary Materials.

Table 2. Fuel variants evaluated in the steam-generator technologies. AHR; *Dichrostachys cinerea*.

Variant	Composition	Type
V1	100% bagasse	single fuel
V2	100% AHR	single fuel
V3	100% <i>Dichrostachys cinerea</i>	single fuel
V4	50% bagasse + 50% AHR	blend
V5	90% AHR + 10% <i>D. cinerea</i>	blend

These five variants cover both individual fuels and binary blends, enabling comparison between the utilization of bagasse alone and its supplementation with external biomass—AHR and *Dichrostachys cinerea*—while isolating the effect of each strategy on the three evaluated dimensions.

2.2. General Structure of the Protocol

The protocol reinterprets sustainability assessment as a sequential three-stage procedure, structured so that the output of each stage feeds the next and culminates in an auditable decision. *Stage 1* defines the set of fuel alternatives and, through the Delphi method, screens the relevant criteria and sub-criteria. *Stage 2* characterizes each alternative through three coupled balances—energy, exergy, and emergy—from which the indicators constituting those criteria are obtained. *Stage 3* integrates these indicators through the analytic hierarchy process (AHP) into a single sustainability ranking and applies an explicit decision rule; if the best alternative does not satisfy the sustainability criterion, a feedback loop revises the fuel blend. Figure 1 summarizes this workflow.

Unlike formulations in which judgment matrices are constructed before the balances are computed, here the Delphi screening and AHP weighting are applied to indicators already calculated in Stage 2, thereby eliminating the circular dependence between criteria and data.

The sequential character and the feedback loop shown in Figure 1 are what confer upon the procedure its nature as a *protocol* rather than a mere calculation: each stage generates the inputs for the next, criteria are weighted only after the indicators have been computed, and the final decision is conditioned on an explicit sustainability threshold. This structure is what makes the procedure reproducible, auditable, and transferable to other sectors and fuels.

2.3. Stage 1—Definition of Alternatives and Criteria Screening (Delphi)

The set of alternatives is composed of the fuel variants listed in Table 2. Criteria screening is carried out through the Delphi method, adopted because it provides a structured, iterative consensus procedure among domain experts that preserves anonymity and controlled feedback, thereby mitigating the dominance and bandwagon effects typical of face-to-face panels. It is particularly suitable when quantitative historical records for weighting the candidate criteria are scarce—as is the case for the joint energy–exergy–emergy characterization of biomass fuels—and when the goal is to converge on a reduced, defensible set of criteria rather than to estimate a population parameter. Unlike purely data-driven weighting schemes such as the Shannon-entropy method—which require a pre-existing decision matrix—Delphi operates upstream, at the criteria-definition stage, and its degree of agreement is objectively quantified through Kendall’s coefficient of concordance [51–53].

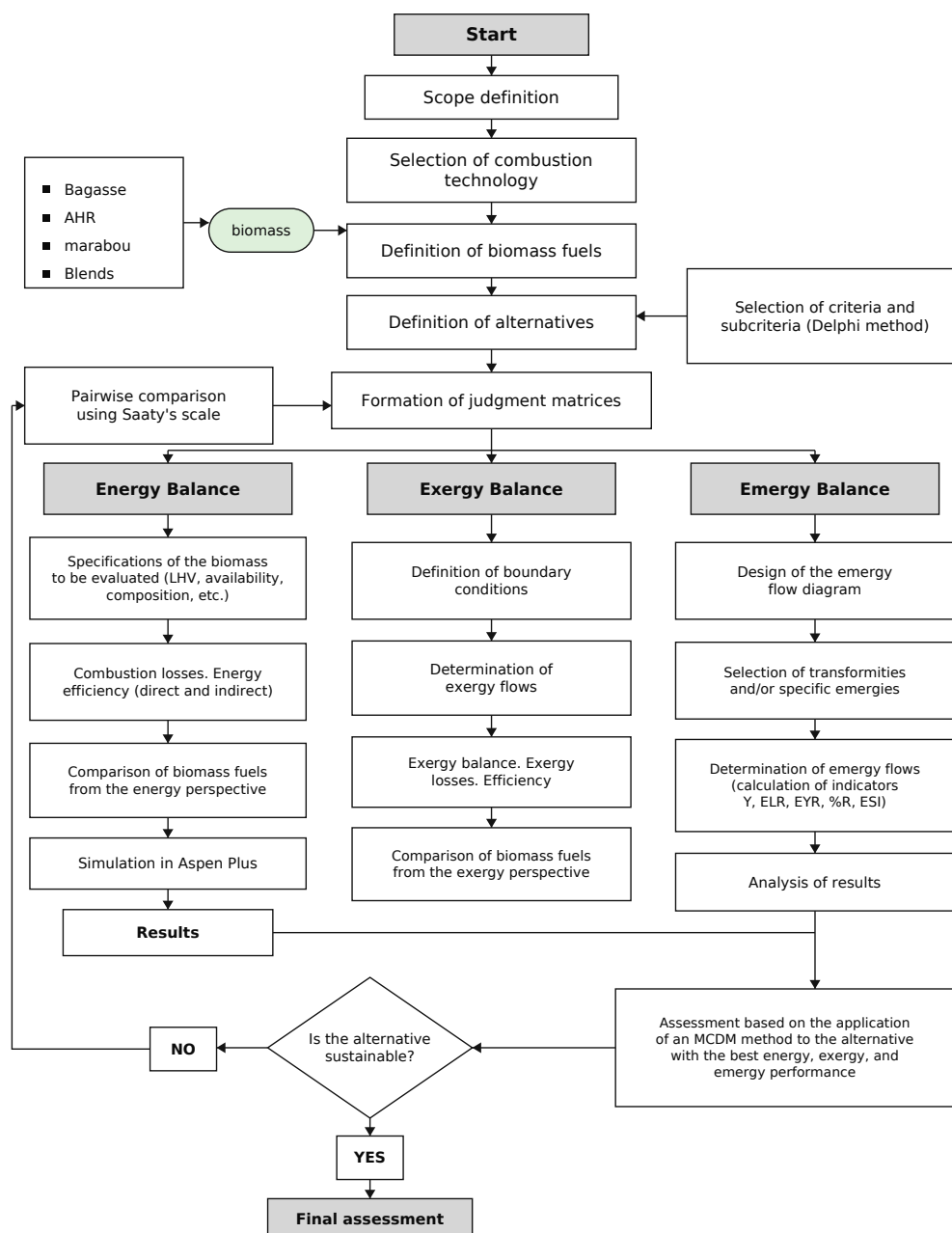


Figure 1. Three-stage assessment protocol. Stage 1 defines fuel alternatives and screens criteria/sub-criteria via the Delphi method; Stage 2 characterizes each alternative through three coupled balances—energy (quantity), exergy (quality), and emergy (environmental cost)—yielding the indicators that act as criteria; Stage 3 integrates the indicators through the analytic hierarchy process (AHP) into a single sustainability ranking governed by an explicit decision rule, with a feedback loop that revises the fuel blend when the sustainability condition is not met. The balances precede criteria weighting, removing the circular dependence between criteria and data.

The selection of experts involved in the criteria screening is based on the competence coefficient K , computed as the semi-sum of a knowledge coefficient K_c and an argumentation coefficient K_a , Equation (1):

$$K = \frac{1}{2}(K_c + K_a), \quad K_c = 0.1 \sum_{i=1}^n \frac{v_{c,i}}{n_c}, \quad (1)$$

where $v_{c,i}$ are the self-assessments of the candidate across the n_c aspects of the questionnaire, and K_a is obtained from the weighted sum of argumentation sources; by construction $K \in (0, 1]$. A candidate's competence is rated as high if $K \geq 0.8$, medium if $0.5 \leq K < 0.8$, and low if $K < 0.5$. The number of experts is determined using Equation (2):

$$m = \frac{p(1-p)k}{i^2}, \quad (2)$$

with p the admissible error proportion, i the precision, and k a constant associated with the confidence level $(1 - \alpha)$. The Delphi method is then applied to screen the criteria: those rated by experts as *important* or *very important* are retained, and the degree of agreement is verified using Kendall's coefficient, Equation (3):

$$W = \frac{12S}{m^2(n^3 - n)}, \quad (3)$$

where S is the sum of squared deviations of the rank sums and n is the number of criteria. In the demonstration, applying Equation (2) with an admissible error proportion $p = 0.01$, precision $i = 0.05$, and confidence level $(1 - \alpha) = 95\%$ yielded a required panel size of approximately 15 experts. A total of 20 candidates—technicians and professionals from different specialties with experience in the sugar industry—were proposed, from which the 15 with the highest competence coefficient K were selected. Applying the screening to an initial set of 15 candidate indicators, the panel retained 12 sub-criteria (rated important, very important, or moderately important), grouped into energy, exergy, and emergy methods and associated with the economic, environmental, and social dimensions of sustainability, with a concordance of $W = 0.796$ [54]. The expert questionnaire and competence-coefficient computations are provided in the Supplementary Materials.

2.4. Stage 2—Coupled Energy–Exergy–Emergy Balances

2.4.1. Energy Balance

The energy efficiency of each variant is determined using both the direct and indirect methods. The indirect method derives it from percentage losses, Equation (4):

$$\eta_{\text{en}} = 100 - (q_2 + q_3 + q_4 + q_5 + q_6), \quad (4)$$

where q_2 corresponds to stack gas losses, q_3 to chemical incomplete combustion, q_4 to mechanical incomplete combustion, q_5 to external cooling losses, and q_6 to the physical heat of slag. The direct method is used as a consistency check, defined as the ratio between the useful heat of the generated steam and the energy input from the fuel. Losses and efficiencies are determined following the standard procedure for steam generators [56] and are cross-validated with process simulation.

2.4.2. Exergy Balance

Defining the steam generator as a control volume, the exergy balance between input and output streams is established such that the destroyed exergy (irreversibility) is the difference between input exergy and output exergy, Equation (5):

$$\dot{E}x_{\text{dest}} = \sum \dot{E}x_{\text{ent}} - \sum \dot{E}x_{\text{sal}}. \quad (5)$$

Exergy efficiency is defined as the ratio between useful exergy—that of the produced steam—and the exergy supplied by the fuel, Equation (6):

$$\psi_{\text{ex}} = \frac{\dot{E}x_{\text{vs}}}{\dot{E}x_{\text{comb}}}. \quad (6)$$

The exergy streams (feedwater, fuel, flue gases, and steam) and losses are determined analytically and through Aspen Plus (AspenTech, Aspen Technology, Inc., Bedford, MA, USA) simulation, and the results are cross-validated against literature reports for similar operating conditions [18].

The process simulation supporting both the energy and exergy balances was developed in Aspen Plus and is reported in detail in [18]; it is summarized here for completeness and is not an original computation of the present work. A zero-dimensional model of the steam generator was built from unit-operation modules with FORTRAN calculator blocks. Thermodynamic properties were evaluated with the Peng–Robinson equation of state with Boston–Mathias modifications (PR–BM). The three biomasses (bagasse, AHR, *D. cinerea*) were represented as non-conventional components, with the HCOALGEN model for the formation enthalpy and specific heat and the DCOALIGT model for density. The combustion chamber was simulated by coupling two reactor blocks from the software library: an RYield reactor that decomposes the non-conventional biomass into its constituent elements, followed by an RGibbs reactor that computes the equilibrium combustion products by Gibbs free-energy minimization, assuming 30% excess air at 27 °C and 1 bar. Steam generation (economizer, evaporator, superheater) was represented through thermal phase-change blocks, with the heat duty computed iteratively from the flue-gas outlet temperature and a feedwater temperature of 80 °C. The zero-dimensional model was validated against the steam-generation index (kg steam/kg bagasse) reported by Rein for three moisture contents, two flue-gas temperatures, and five steam pressure–temperature levels. The full block description is provided in the Supplementary Materials.

2.4.3. Emergy-Based Assessment

Emergy synthesis begins with the construction of the emergy flow diagram and the classification of system inputs into renewable resources R , non-renewable resources N , economic materials M , and economic services F , whose sum yields the total emergy Y [8]. Based on literature-defined transformities and the one calculated for *Dichrostachys cinerea*, emergy indicators are obtained. The transformity Tr relates the total emergy input to the energy of the product E_p , Equation (7), and the specific emergy Em relates it to the product mass P :

$$Tr = \frac{Y}{E_p}, \quad Em = \frac{Y}{P}. \quad (7)$$

Emergy sustainability is evaluated through the renewability ratio, emergy yield ratio, environmental loading ratio, and emergy sustainability index, Equation (8) [9]:

$$\%R = \frac{R}{Y}, \quad EYR = \frac{Y}{F}, \quad ELR = \frac{N + M + F}{R}, \quad ESI = \frac{EYR}{ELR}. \quad (8)$$

The procedure for determining *Dichrostachys cinerea* transformity (dry mass yield, energy yield, and system emergy) is detailed in the Supplementary Materials.

2.5. Stage 3. Multicriteria Integration (AHP) and Decision Rule

The indicators obtained in Stage 2 are integrated using the analytic hierarchy process (AHP). Pairwise comparisons are performed using Saaty's nine-point scale [36], and the local priority vector (LPV) is obtained by normalizing the columns of the judgment matrix and averaging the rows. The consistency of each matrix is verified through the principal eigenvalue $\lambda_{\max}$, the consistency index CI, and the consistency ratio CR, Equation (9) [35,36]:

$$A \cdot w = \lambda_{\max} w, \quad CI = \frac{\lambda_{\max} - n}{n - 1}, \quad CR = \frac{CI}{RI}, \quad (9)$$

where RI is the random index corresponding to the order n of the matrix; a matrix is considered consistent when CR does not exceed the accepted threshold for its size. The global priority of each alternative a is synthesized as the weighted sum of its scores $s_{a,c}$ with respect to each criterion c and the weight w_c of that criterion, Equation (10) [35]:

$$P_a = \sum_c w_c s_{a,c}. \quad (10)$$

The final decision is formalized through an explicit rule that combines the AHP ranking with an emergy sustainability threshold. An alternative is considered sustainable if it attains the highest global priority value P_a and its emergy sustainability index satisfies $ESI \geq 1$. It should be noted that the $ESI \geq 1$ threshold was originally established at the system level and that its universality is debated in the emergy literature, since its interpretation depends on the adopted system boundary and scale. In this protocol the boundary is set at the steam-generation unit; accordingly, the threshold is used as a *relative screening criterion* to compare fuel alternatives evaluated under identical system boundaries, rather than as an absolute verdict on the sustainability of the component in isolation. Because all variants share the same boundary, the comparative conclusion is unaffected by this reinterpretation. If the top-ranked alternative does not satisfy the condition $ESI \geq 1$, the feedback loop in Figure 1 is activated, and the fuel blend composition is revised.

2.6. Robustness and Uncertainty Layer

The stability of the ranking is assessed through a two-level robustness layer. In the first level, uncertainty in the judgments is propagated by perturbing criterion and sub-criterion weights around their assigned values using Dirichlet sampling, and the ranking is recomputed over a large number of Monte Carlo iterations, reporting the frequency with which each alternative attains each rank position (rank acceptability index). This first level follows the logic of stochastic multicriteria acceptability analysis (SMAA), which explores the weight space to characterize the valuations that make each alternative the preferred one [57,58]. In the second level, the AHP ranking is compared against those obtained using alternative multicriteria methods—TOPSIS and PROMETHEE—applied to the same indicator matrix [37,38], and agreement is evaluated using Spearman's rank correlation coefficient. As a complementary analysis, a sustainability critical weight is determined—the value of the emergy weight below which the best-ranked alternative changes—in order to delimit the weight range over which the decision remains stable.

Formally, in the first level, weights are sampled from a Dirichlet distribution centered on the assigned vector $\mathbf{w}^0$, Equation (11) [58]:

$$\mathbf{w}^{(k)} \sim \text{Dir}(\kappa \mathbf{w}^0), \quad k = 1, \dots, N, \quad (11)$$

where $\kappa > 0$ is a concentration parameter that controls the dispersion around $\mathbf{w}^0$, and each sample satisfies $\sum_c w_c^{(k)} = 1$ with $w_c^{(k)} \geq 0$. In the demonstration, the concentration parameter was set to $\kappa = 50$ —which produces a dispersion around the assigned weight vector consistent with the plausible uncertainty in expert judgments—with $N = 10,000$ samples and a fixed random seed to guarantee exact reproducibility. To verify that the verdict does not depend on this choice, a sensitivity analysis was performed over $\kappa \in \{10, 50, 200\}$, spanning from diffuse to concentrated weight distributions. For each sample, the global priority $P_a^{(k)}$ (Equation (10)) is recomputed and each alternative is ranked. The rank acceptability index $b_{a,r}$ —the frequency with which alternative a occupies rank position r —is estimated using Equation (12) [57]:

$$b_{a,r} = \frac{1}{N} \sum_{k=1}^N \mathbb{I}[\text{rank}(P_a^{(k)}) = r], \quad (12)$$

where $\mathbb{I}[\cdot]$ is the indicator function. In the energy block, an alternative a^* Pareto-dominates another alternative a when Equation (13) holds [59]:

$$\%R_{a^*} \geq \%R_a \wedge \text{EYR}_{a^*} \geq \text{EYR}_a \wedge \text{ELR}_{a^*} \leq \text{ELR}_a, \quad (13)$$

with at least one strict inequality. If a^* dominates all other alternatives *within the energy block*, then no combination of non-negative weights applied to those energy indicators can displace it from the first position of that block, which constitutes an analytical guarantee of stability for the dominant criterion. To bound the range of weights in which the ranking remains unchanged, the trade-off between efficiency (energy) and sustainability (ESI) is parameterized through a weight $w_{\text{sus}} \in [0, 1]$, and the critical sustainability weight is defined according to Equation (14):

$$w^* = \min \left\{ w_{\text{sus}} \in [0, 1] : \arg \max_a P_a(w) = V1 \text{ for all } w \geq w_{\text{sus}} \right\}. \quad (14)$$

Finally, the agreement between the AHP ranking and those obtained using TOPSIS and PROMETHEE II is quantified using Spearman's rank correlation coefficient, Equation (15):

$$\rho = 1 - \frac{6 \sum_{i=1}^m d_i^2}{m(m^2 - 1)}, \quad (15)$$

where d_i is the difference between the ranks of alternative i under two methods, and m is the number of alternatives.

3. Results

The protocol is applied to the Cuban sugar industry using the two steam-generation technologies and the fuel variants listed in Table 2. The results are organized according to the protocol stages: the two balances of Stage 2 (Sections 3.1 and 3.2), the multicriteria integration of Stage 3 (Section 3.3), and the robustness analysis (Section 3.4). As this is a single-case demonstration, the balance values are presented as an illustration of the protocol operation and are supported by the sources that report them in detail [18,28,54].

3.1. Energy and Exergy Performance

The highest energy efficiencies corresponded to the complementary fuels. From simulation, 100% *Dichrostachys cinerea* (V3) and 100% AHR (V2) achieved 87.48% and 87.31%, respectively; the bagasse–AHR blend (V4) averaged 84.95%, which is 3.3% higher than pure bagasse combustion; and the V5 blend (90% AHR–10% *Dichrostachys cinerea*) reached 85.82% using the direct method [18]. Bagasse (V1) showed the lowest energy efficiencies: 77.67% (indirect method) and 78.5% (direct method) analytically, and 82.62% and 83.99% from simulation for the cases associated with the Retal and VU-40 technologies, respectively. Across all variants, the VU-40 technology outperformed the Retal system by approximately 5% due to its higher operating pressure (Figure 2) [54].

The simulation-based efficiencies were adopted for the AHP integration because they close the balance under the real fuel composition and homogeneous operating conditions across all variants, ensuring the comparability of the indicators feeding the decision matrix; the analytical indirect-method values, based on normative losses, are retained as a consistency check. The gap of up to six percentage points between both approaches (e.g., 77.67% analytical vs. 82.62% simulated for bagasse in the Retal unit) reflects this methodological

difference—normative loss coefficients versus a mass- and energy-balance closure with real composition—rather than an inconsistency in the data.

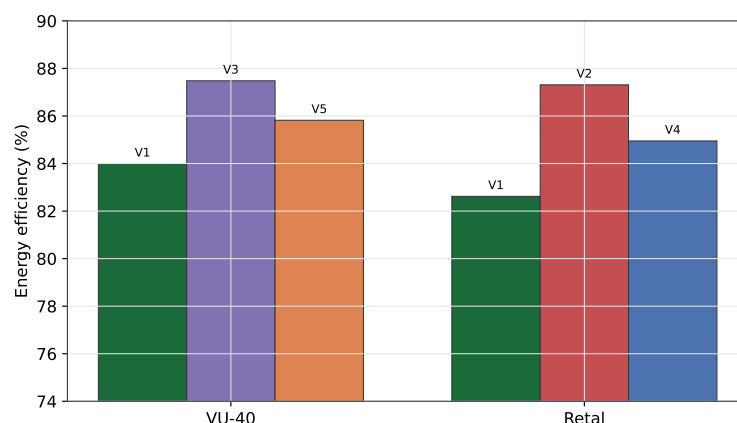


Figure 2. Energy efficiency of the fuel variants by steam-generator technology. The complementary fuels (AHR, *Dichrostachys cinerea*) achieve the highest energy efficiency, whereas bagasse (V1) is the least efficient. The high-pressure VU-40 generator outperforms the Retal type for all variants.

Figure 2 reveals a consistent pattern across both technologies: complementary fuels (*Dichrostachys cinerea* and AHR) systematically outperform bagasse in terms of energy efficiency, and the difference between technologies (VU-40 vs. Retal) is smaller than the difference between fuels. This result already suggests that the decision on the most suitable fuel cannot be based solely on the amount of energy recovered.

From an exergy perspective, efficiencies ranged between 25.2% and 35.4%. Bagasse (V1) exhibited the highest exergy destruction, with an exergy efficiency of 28.35% in the VU-40 unit and 26.69% in the Retal unit; the bagasse–AHR blend (V4) reached 32.18%, and 100% AHR (V2) reached 37.68% in the Retal generator, while in the VU-40 generator 100% *Dichrostachys cinerea* (V3) reached 31.81% and the V5 blend achieved 29.11%. In the VU-40 generator, *Dichrostachys cinerea* increased exergy efficiency by approximately 10.9% compared to bagasse, and V1 showed a 5.9% increase in the higher-pressure technology relative to the lower-pressure one. The contrast between both lenses is already evident: complementary fuels are energetically—and, in exergy terms, also—superior to bagasse. Table 3 summarizes the energy and exergy performance by variant and technology.

Table 3. Energy and exergy efficiency of the fuel variants by steam-generator technology. Energy efficiency from process simulation; exergy efficiency from the exergy balance. Values in blue were completed or corrected in this revision.

Technology	Variant	Energy Efficiency (%)	Exergy Efficiency (%)
VU-40	V1 (bagasse)	83.99	28.35
VU-40	V3 (<i>Dichrostachys cinerea</i>)	87.48	31.81
VU-40	V5 (AHR + <i>Dichrostachys cinerea</i>)	85.82	29.11
Retal	V1 (bagasse)	82.62	26.69
Retal	V2 (AHR)	87.31	37.68
Retal	V4 (bagasse + AHR)	84.95	32.18

The joint reading of Table 3 provides the first indication of the disassociation that the protocol seeks to capture. The gap between energy efficiency (quantity) and exergy efficiency (quality)—on the order of fifty percentage points—quantifies the irreversible degradation of fuel content during combustion, a loss of quality that the first-law balance alone does not reveal. Moreover, the ranking of alternatives changes depending on the lens:

while complementary fuels lead in energy efficiency, bagasse exhibits the lowest exergy efficiency in both technologies, anticipating that neither thermodynamic magnitude, taken in isolation, is sufficient to rank sustainability.

3.2. Emergy Synthesis

For *Dichrostachys cinerea*, a total emergy of 1.76×10^{15} seJ/year was determined. Tables 4 and 5 summarize the emergy indicators by fuel variant for the VU-40 and Retal technologies, respectively, and Figure 3 presents their graphical representation. In both technologies, bagasse (V1) exhibited the best emergy performance: the highest renewability ratio (%R = 62.67 in VU-40; 58.04 in Retal), the highest emergy yield ratio (EYR = 3.53 and 2.38), and the lowest environmental loading ratio (ELR = 2.92 and 0.72), resulting in the highest emergy sustainability index (ESI = 5.96 and 5.30). At the opposite extreme, 100% AHR (V2) in the Retal technology showed ESI = 0.40, below the sustainability threshold (ESI < 1), indicating that, by itself, it does not constitute a sustainable long-term contribution. The remaining variants (ESI between 2.72 and 3.91 in VU-40; 1.49 for the bagasse–AHR blend in Retal) fall within the range of medium-term sustainability [8,9].

Table 4. Emergy indicators for the VU-40 steam generator (variants V1, V3, V5). %R: renewability ratio; EYR: emergy yield ratio; ELR: environmental loading ratio; ESI: emergy sustainability index.

Indicator	V1	V3	V5
Renewability ratio (%R)	62.67	42.54	50.22
Emergy yield ratio (EYR)	3.53	2.01	2.46
Environmental loading ratio (ELR)	2.92	3.97	3.01
Emergy sustainability index (ESI)	5.96	2.72	3.91

Table 5. Emergy indicators for the Retal-type steam generator (variants V1, V2, V4).

Indicator	V1	V2	V4
Renewability ratio (%R)	58.04	23.58	39.55
Emergy yield ratio (EYR)	2.38	1.31	2.28
Environmental loading ratio (ELR)	0.72	3.24	1.53
Emergy sustainability index (ESI)	5.30	0.40	1.49

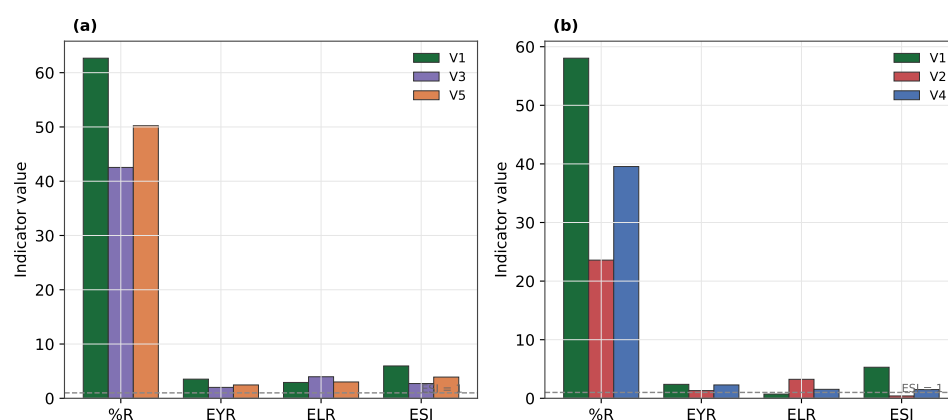


Figure 3. Emergy indicators (%R, EYR, ELR, ESI) by fuel variant for (a) the VU-40 and (b) the Retal steam generators. Bagasse (V1) shows the highest renewability and emergy yield, the lowest environmental load, and consequently the highest emergy sustainability index in both technologies. The dashed line marks the sustainability threshold at ESI = 1.

Figure 3 makes the decisive contrast of the study explicit: whereas in energy efficiency bagasse appeared as the least favorable fuel, at the emergy level it performs best across all

four metrics and in both technologies. This is the first clear indication of the disassociation between efficiency and sustainability that the protocol quantifies in the integration stage, and it is explained by the fact that bagasse is obtained within the process itself, without the environmental cost associated with the mobilization of external biomass.

3.3. Multicriteria Integration

The selected Delphi panel (15 experts; Kendall's concordance $W = 0.796$) retained 12 subcriteria distributed across the energy, exergy, and emergy methods. The AHP weighting of the criteria assigned dominant importance to the emergy method over exergy and energy, with priority vectors of 0.539, 0.297, and 0.164, respectively, and a consistency ratio $CR = 0.008$, well below the accepted threshold [36]. Among subcriteria, energy efficiency (En1, 66%), exergy efficiency (Ex2, 75%), and the emergy sustainability index (ESI, 41%) were dominant [54].

The global ranking identifies bagasse (V1) as the most sustainable alternative in both technologies (Table 6 and Figure 4): a global priority of 0.45 compared to 0.28 (V2) and 0.25 (V4) in the Retal steam generator, and 0.53 compared to 0.25 (V3) and 0.22 (V5) in the VU-40 unit. Applying the decision rule (Section 2.5), bagasse simultaneously satisfies the highest global priority and the condition $ESI \geq 1$ in both technologies, so it is confirmed as a sustainable fuel without requiring activation of the mixture-revision feedback loop.

The central result of the case is the *disassociation between efficiency and sustainability*. Although *Dichrostachys cinerea* and AHR are the most energy-efficient fuels, bagasse emerges as the most sustainable because the emergy criterion—which penalizes the environmental cost of mobilizing additional biomass, including harvesting and transport—dominates the decision, concentrating more than half of the total weight (0.539). The protocol makes explicit that “higher efficiency” does not necessarily imply “higher sustainability”, and that the final conclusion depends transparently and auditable on the weighting structure of the criteria.

Table 6. Criteria weights (AHP) and global sustainability priorities of the fuel variants by technology. CR: consistency ratio.

(a) Criteria weights (AHP, CR = 0.008)		
Energy method		0.164
Exergy method		0.297
Emergy method		0.539
(b) Global priorities (top-3 per technology)		
Technology	Variant	Global priority
Retal	V1 (bagasse)	0.45
Retal	V2 (AHR)	0.28
Retal	V4 (bagasse + AHR)	0.25
VU-40	V1 (bagasse)	0.53
VU-40	V3 (<i>Dichrostachys cinerea</i>)	0.25
VU-40	V5 (AHR + <i>Dichrostachys cinerea</i>)	0.22

Figure 4 summarizes why bagasse emerges as the most sustainable option despite its lower efficiency: panel (a) shows that the emergy criterion dominates the weighting structure (0.539), exceeding both exergy and energy, and panel (b) shows that this dominance translates directly into the first position of bagasse in both technologies. The ranking is therefore not an opaque outcome, but a direct and traceable consequence of a predefined weighting structure.

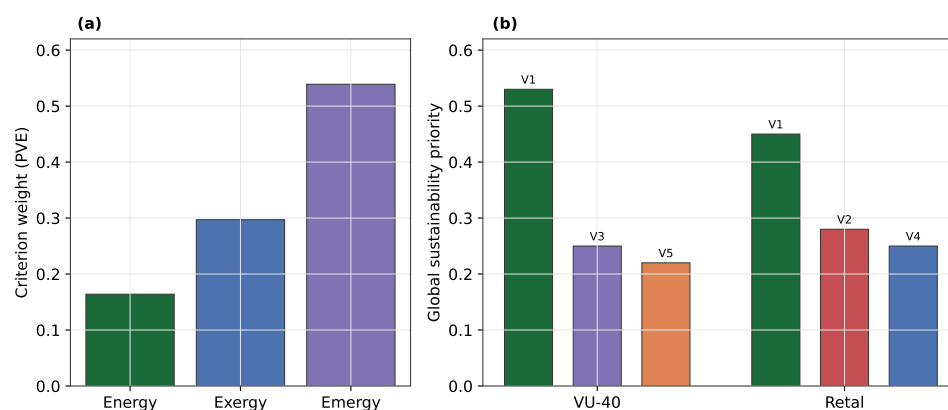


Figure 4. (a) AHP criteria weights, with the emery method dominating (0.539) over exergy (0.297) and energy (0.164); the judgement matrix is consistent (CR = 0.008). (b) AHP global sustainability priorities (top-3 alternatives per technology); bagasse (V1) ranks first in both the Retal and the VU-40 generators.

3.4. Robustness of the Decision

The stability of the ranking was examined at the two levels described in Section 2.6. Within the emery block—the dominant criterion—bagasse (V1) is Pareto-dominant over the independent emery indicators (%R and EYR to be maximized; ELR to be minimized) in both technologies. It should be emphasized that this dominance holds *within the emery block only*; in the full indicator space bagasse does not Pareto-dominate, since it exhibits the lowest energy and exergy efficiencies. Consequently, the global stability of the ranking does not rest on full-space dominance but on the weight assigned to the dominant emery criterion, as confirmed by the weight-sensitivity analysis below. Consistently, the Monte Carlo simulation ($N = 10,000$, weights sampled from a Dirichlet distribution with $\kappa = 50$) assigns bagasse a probability of ranking first equal to 1.000 in both technologies (Figure 5b), with a stable lower ordering ($V5 \succ V3$ in VU-40 and $V4 \succ V2$ in Retal). This first-place probability remained equal to 1.000 across the entire sensitivity range $\kappa \in \{10, 50, 200\}$, confirming that the verdict is insensitive to the concentration parameter of the Dirichlet distribution. The cross-method comparison confirmed independence from the aggregation scheme: rankings obtained via weighted sum, TOPSIS, and PROMETHEE II were identical, with Spearman rank concordance coefficients equal to 1.000 across all method pairs.

Regarding the partial correlation between the energy and exergy criteria noted in the Discussion, the coefficient measured across the five variants in both technologies is moderate (Pearson $r = 0.78$, $R^2 = 0.61$), rather than negligible. To verify that this partial overlap does not drive the verdict through implicit double counting, an additional scenario was computed in which the energy and exergy criteria are collapsed into a single composite thermodynamic criterion (combined weight $0.164 + 0.297 = 0.461$), leaving emery as the second criterion (0.539). Under this grouped structure—which eliminates any possibility of double-counting the thermodynamic dimension—bagasse (V1) remains the top-ranked alternative in both technologies, confirming that the sustainability verdict is not an artifact of treating the two thermodynamic lenses as separate criteria.

At a higher level, the trade-off analysis between energy efficiency and sustainability (ESI) yielded a critical sustainability weight of $w^* = 0.050$ for the VU-40 steam generator and $w^* = 0.026$ for the Retal steam generator (Figure 5a). In other words, assigning a weight greater than 5% and 2.6%, respectively, to the emery dimension is sufficient for bagasse to become the best alternative. Since the effective emery weight (0.539) is nearly ten times these thresholds, bagasse remains the best option in 95.0% and 97.4% of the weight space for each technology. This result is consistent with the equal-weight scenario

reported for the same case, in which bagasse retains the first position (38.17%), followed by the bagasse–AHR blend (31.79%) and 100% AHR (29.04%) [54]. Overall, the sustainability verdict of the protocol is robust with respect to both uncertainty in expert judgments and the choice of aggregation method.

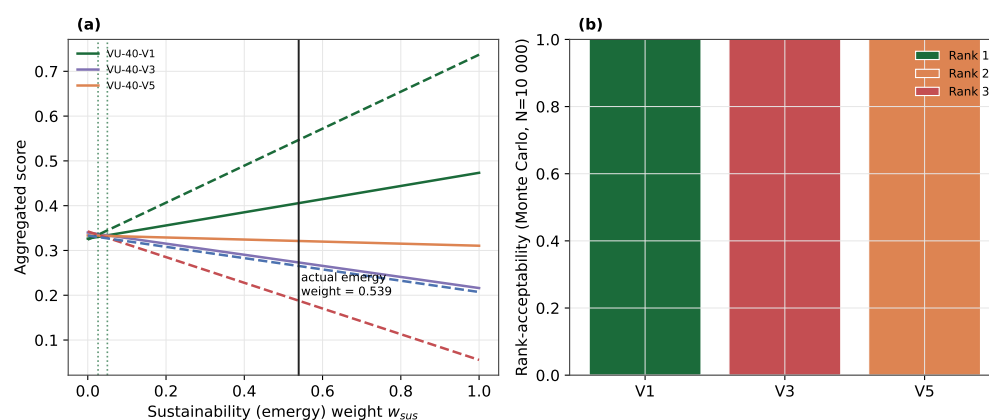


Figure 5. Robustness of the sustainability verdict. (a) Top-level weight sensitivity between efficiency (energy) and sustainability (ESI); bagasse (V1) becomes and remains the top alternative once the sustainability weight exceeds the critical value w^* (0.050 for VU-40, 0.026 for Retal), far below the actual energy weight (0.539, solid line). (b) Monte Carlo rank-acceptability ($N = 10,000$, $\kappa = 50$) within the energy block for the VU-40 steam generator; bagasse attains rank 1 with probability 1.000.

Figure 5 shows that this conclusion is not fragile. Panel (a) indicates that bagasse leads the ranking over nearly the entire weight space—the reversal threshold is roughly an order of magnitude lower than the effective energy weight—and panel (b) confirms that its first position is maintained across virtually all 10,000 Monte Carlo simulations. The sustainability verdict is therefore robust against the inherent subjectivity of weight assignment and is not an artifact of a particular weighting choice.

3.5. Final Decision and Cycle Closure

The protocol is, above all, a *decision-making* procedure; its final stage must therefore produce a selection. The decision rule formalized in Stage 3 (Section 2.5) selects, for each technology, the alternative with the highest global priority that also satisfies the sustainability condition $ESI \geq 1$. If the top-ranked alternative does not meet this condition, the protocol does not issue a selection; instead, it returns to Stage 1 to redefine the fuel blends (feedback loop). Table 7 applies this rule to the case study. For the VU-40 steam generator, the highest-ranked alternative is bagasse (V1), with a global priority of 0.53 and $ESI = 5.96$; for the Retal steam generator, the same alternative is again selected, with priority 0.45 and $ESI = 5.30$. In both cases, the condition $ESI \geq 1$ is satisfied with a wide margin, so the rule produces a direct selection and does not activate the feedback loop.

Table 7. Closure of the decision cycle: application of the decision rule (highest global priority subject to $ESI \geq 1$) for each steam-generation technology.

Technology	Top-Ranked Alternative	Global Priority	ESI	$ESI \geq 1$	Decision
G.V. VU-40	V1 (bagasse)	0.53	5.96	Yes	Selected
Retal-type	V1 (bagasse)	0.45	5.30	Yes	Selected

Consequently, the sustainability decision that closes the protocol for this case is unambiguous: bagasse (V1) is the selected fuel for both steam-generation technologies. The relevance of the $ESI \geq 1$ condition becomes evident when noting that not all efficient alternatives satisfy it: in the Retal steam generator, 100% AHR (V2)—the second most efficient

option under the first-law criterion—yields $ESI = 0.40 < 1$. Hence, had it been the top-ranked alternative, it would have been rejected as unsustainable, and the protocol would have required reconfiguring the fuel blend before issuing any recommendation. Since the final selection corresponds to bagasse and the robustness analysis (Section 3.4) confirms that this dominance persists over more than 95% of the weight space and across all three aggregation methods, the decision cycle closes with a stable, traceable, and reproducible recommendation without the need for further iterations.

4. Discussion

The central finding of this demonstration—the disconnection between efficiency and sustainability—deserves careful interpretation. Complementary fuels (*Dichrostachys cinerea* and AHR) outperform bagasse both in energy efficiency (up to 87.48% versus approximately 83%) and, in exergy efficiency; however, bagasse emerges as the most sustainable option in both technologies. The explanation is structural: the emergy criterion accounts for more than half of the decision weight (0.539), and under this lens bagasse dominates because it is obtained within the sugar production process itself, without the additional environmental cost of cultivating, collecting, and transporting external biomass. These upstream processes increase material and service inputs from the economy, thereby penalizing AHR and *Dichrostachys cinerea* in emergy terms. The protocol does not conceal this dependence; rather, it makes it explicit and auditable, showing that the final verdict is not an intrinsic property of the fuel but the outcome of a declared weighting structure. The robustness analysis further clarifies the sensitivity of this conclusion: bagasse would cease to be the preferred option only if the emergy weight fell below approximately 5%, placing the result far from any plausible reversal threshold.

It is useful to contrast the values obtained in this case with those reported in the literature with a similar approach, which allows their plausibility to be assessed. From an exergy perspective, the efficiency obtained for bagasse combustion (26.7–28.4%) and the identification of the highest irreversibilities in the boiler are consistent with exergy and exergo-environmental analyses of bagasse-based cogeneration systems: Cavalcanti et al. [3] report that the boiler furnace accounts for nearly 62% of the total exergy destruction of the system, and exergy studies of sugarcane power plants consistently identify combustion as the stage with the highest degradation of energy quality [15].

From an emergy perspective, the contrast is even more revealing: the emergy sustainability index values obtained for bagasse ($ESI = 5.30$ – 5.96) are substantially higher than those reported for cultivated biomass used for energy purposes. Edrisi et al. [60] report ESI values between 0.02 and 1.04 for energy crops grown on marginal lands in India, typically below the sustainability threshold ($ESI < 1$). The reason is structural and consistent with the broader emergy literature on biomass systems: residues used within their own production chain, such as bagasse, exhibit significantly higher emergy performance than dedicated energy crops, which rely heavily on purchased inputs and economic services [61]. This cross-source agreement supports the central outcome of the protocol: the high sustainability of bagasse is not an artifact of the weighting scheme, but an emergy property of utilizing an internal by-product stream.

A second issue concerns the incommensurability among the three perspectives. Energy and exergy are partially correlated thermodynamic quantities (measured Pearson $r = 0.78$ across the evaluated variants), both describing the utilization of the fuel content, whereas emergy belongs to a different accounting domain, namely the cumulative environmental investment required to make a resource available. Aggregating them into a single index without structure may introduce implicit double counting of thermodynamic contributions. The protocol addresses this issue in two complementary ways: by keeping the three

dimensions as separate weighted criteria rather than collapsing them, and by verifying, through the grouped-criterion scenario reported in Section 3.4, that the ranking is invariant when energy and exergy are merged into a single thermodynamic criterion. A related caveat concerns the $ESI \geq 1$ threshold: as noted in Section 2.5, its interpretation is scale- and boundary-dependent, so in this protocol it operates as a relative screening criterion among alternatives sharing the same system boundary (the steam-generation unit) rather than as an absolute sustainability verdict for the component. The robustness layer confirms that the ranking does not depend on the aggregation method.

Table 8 positions the contribution with respect to existing approaches. Bagasse cogeneration assessment has traditionally been addressed through exergy analysis [15], exergo-environmental and life cycle assessment studies [3,20], or thermoeconomic analysis [19]. Each approach provides a valuable but partial perspective, without an explicit decision rule that translates results into a sustainability ranking. The integration of the three methods through multicriteria decision-making has been recently proposed for the Cuban sugar industry via Delphi-AHP [54] and AHP-TOPSIS [55], which established decision procedures but not a fully formalized protocol. The contribution of this work—based on the conducted review—is the end-to-end formalization: the sequence balances→screening→ranking, the explicit decision rule with the $ESI \geq 1$ threshold, and the robustness layer (Monte Carlo simulation, multi-method comparison, and Pareto dominance), framed as a generalizable procedure.

In aggregate, Table 8—which compiles sixteen representative studies—shows that the contribution of this work does not lie in an isolated numerical result—the exergy efficiency of bagasse is of the same order as those reported in the cogeneration literature for bagasse, while its emergy indicators are substantially higher due to its nature as an internal residue—but rather in the last column: the integration, within a single auditable procedure, of the three analytical lenses, the explicit decision rule with an $ESI \geq 1$ threshold, and the robustness layer, which is absent in previous approaches.

Beyond the case study, the proposed protocol has practical implications for the sugar industry at a global scale, a sector present in more than one hundred countries. In practice, decisions regarding which biomass to combust and under which technology are often based solely on efficiency or short-term cost considerations. By making explicit that the most energy-efficient option is not necessarily the most sustainable, and by providing an auditable procedure to balance quantity, quality, and environmental cost with robustness guarantees, the protocol offers any sugar mill worldwide a transparent and comparable decision-support tool. Its transferability is not limited to sugarcane: any system requiring the selection of biomass fuels or their blends can apply the same three-stage logic.

The study has limitations that should be acknowledged. First, it is a single-case demonstration: although the protocol is general, its application here is restricted to two technologies and five fuel variants within the Cuban sugar industry, and thus the numerical results should not be directly extrapolated to other contexts. Second, emergy results depend on the adopted transformities; in particular, the transformity of *Dichrostachys cinerea* must be estimated carefully to avoid double counting solar radiation and precipitation contributions, which are not independent, and with consistent moisture content between the mass balance and the lower heating value. Third, the robustness layer perturbs criterion weights but treats input indicators as deterministic; a natural extension would be to propagate uncertainty also in the underlying thermodynamic and emergy indicators. These limitations do not affect the logic of the protocol itself, which constitutes the main contribution, but rather the scope of the numerical illustration presented here.

Table 8. Comparison with sixteen representative studies on the energy, exergy, emergy, or multi-criteria assessment of biomass and sugar-industry energy systems. No prior study integrates the three thermodynamic–environmental perspectives with multicriteria decision-making, an explicit sustainability decision rule, and a robustness layer. Eff.: efficiency; therm.: thermoeconomic.

Study	Feedstock/System	Analytical Lenses	Key Reported Result or Focus	Integrated Rule & Robustness
[16]	Sugarcane (Zimbabwe)	Energy	Cogeneration export potential of the sugar industry	No
[15]	Sugar mill cogeneration	Energy, exergy	Boiler is the main source of exergy destruction	No
[19]	Sugar–ethanol–electricity	Energy, exergy, therm.	Thermoeconomic optimization of cogeneration	No
[3]	Bagasse cogeneration	Energy, exergy, LCA	System exergy efficiency 18.73%; furnace $\approx$ 62% of destruction	No
[17]	CHP plants	Energy, exergy, economic	Indicators for cogeneration potential evaluation	No
[20]	Bagasse electricity (Brazil)	LCA	Life-cycle impacts of bagasse power	No
[21]	Sugar & electricity (India)	LCA	LCA across cultivation/cogeneration scenarios	No
[22]	Bagasse vs. ethanol	LCA	Comparative life-cycle environmental benefits	No
[23]	Biomass IGCC + CO ₂ capture	LCA	LCA of biomass gasification combined cycle	No
[24]	Rye bioenergy electricity	LCA + N balance	Coupling soil nitrogen balance with LCA	No
[25]	Bioenergy systems	LCA (review)	Critical review of bioenergy LCA practice	No
[26]	Electricity production systems	Emergy	Emergy indices and environmental loading	No
[61]	Biomass resources	Emergy (review)	Dedicated crops unsustainable; residues recover more	No
[60]	Energy crops, marginal lands	Emergy	ESI 0.02–1.04 (crops typically below unity)	No
[54]	Cuban sugar boilers	Energy, exergy, emergy, MCDM	Delphi–AHP ranking of biomass fuels	Method only
[55]	Sugar-boiler combustion	Emergy, MCDM	AHP–TOPSIS ranking of combustion options	Method only
This work	Cuban sugar boilers (2 technologies, 5 fuels)	Energy, exergy, emergy, MCDM	Bagasse most sustainable (ESI 5.30–5.96) despite lower efficiency	Yes

5. Conclusions

A generalizable protocol was formalized for the sustainability assessment of biomass as fuel, integrating in three sequential stages the energy (quantity), exergy (quality), and emergy (environmental cost) analyses through multi-criteria decision-making. The framework incorporates two elements absent from previous approaches: an explicit decision rule with an emergy sustainability threshold and a robustness layer based on Monte Carlo simulation and multi-method comparison.

In the demonstration applied to the Cuban sugar industry, the AHP weighting scheme ranked the emergy criterion above the exergy and energy criteria (0.539, 0.297, and 0.164; CR = 0.008), and bagasse emerged as the most sustainable alternative in both technologies, despite not being the most energy-efficient option. The robustness analysis showed that this conclusion is stable: bagasse dominates the emergy indicators in the Pareto sense within the emergy block, attains a unit probability of ranking first under weight perturbation—invariant over the concentration range $\kappa \in \{10, 50, 200\}$, remains invariant across aggregation methods (Spearman = 1.000 between AHP, TOPSIS, and PROMETHEE) and under the collapse of energy and exergy into a single thermodynamic criterion, and retains its top position in more than 95% of the weight space.

The transferable contribution is not the numerical results of the case study—which serve only to illustrate the operation of the protocol—but rather the formalized logic that links thermodynamic and emergy balances to an auditable sustainability decision. Future work will proceed along four lines. First, the protocol will be applied to non-sugarcane feedstocks—such as forestry residues, energy crops, and the organic fraction of municipal solid waste—to test its transferability with independent data. Second, alternative screening and aggregation methods (Best–Worst Method, DEMATEL, fuzzy-AHP, and outranking approaches) will be incorporated and compared to assess the sensitivity of the sustainability verdict to the methodological choice. Third, full probabilistic uncertainty will be propagated not only through the criteria weights but also through the underlying thermodynamic and emergy indicators. Fourth, a temporal dimension will be added to capture the seasonal availability of biomass and the inter-annual variability of transformities.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/biomass6040061/s1>, S1. Characterization of the biomass fuels; S2. Steam-generator technical specifications; S3. Expert panel and Delphi screening; S4. Aspen Plus process model; S5 Reproducibility of the robustness layer.

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Abbreviations

The following abbreviations are used in this manuscript:

AHP	Analytic Hierarchy Process
AHR	Agricultural Harvest Residues
CI	Consistency Index
CR	Consistency Ratio
ELR	Environmental Loading Ratio
ESI	Emergy Sustainability Index
EYR	Emergy Yield Ratio
MCDM	Multi-Criteria Decision-Making
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
PVE	Local Priority Vector
RI	Random Index
SMAA	Stochastic Multicriteria Acceptability Analysis
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
Tr	Transformity

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