Techno-economic analysis and exergo-environmental performance of integrated first- and second-generation bioethanol production plants through biochemical and thermochemical conversion pathways

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Abstract:

Driven by a range of bioenergy sustainability challenges, advanced conversion technologies are required to reduce costs, environmental impacts, and increase the productivity/process efficiency to continue the transition of lignocellulosic biofuel production from pilot scales to industrial implementation. Thus, biorefinery technologies could play an important role to produce a comprehensive range of marketable products in a sustainable way from widely available lignocellulosic residues.

This study analyses the integrated first (1G) and second-generation (2G) ethanol production plants via biochemical and thermochemical pathways to improve sustainability-related indexes of sugarcane-based biorefineries in Brazil. In this context, the biochemical conversion process evaluated includes a pre-treatment step followed by enzymatic hydrolysis, whereas the selected thermochemical pathways focuses on the transformation of synthesis gas into electricity.

The integrated 1G + 2G process designs (combining biochemical and thermochemical pathways) for bioethanol production from sugarcane bagasse aiming to develop a thermodynamic-based approach for integrating large resources use efficiency with advanced conversion technologies from a technical, economic and environmental perspective. Thus, several techno-economic and environmental performance parameters are using in the assessment: *i). Energy and exergy efficiency, ii). Average unitary exergy cost (AUEC), iii). Irreversibilities/Exergy$_{products}$ ratio, iv). Global CO_2 emissions, v). CAPEX (capital expenditure) and OPEX (operational expenditure).*

Results regarding the technical conversion of these systems indicated that the higher exergy efficiency (37%) was presented in the integrated 1G + 2G biochemical process and consequently a lower average unitary exergy cost (AUEC=2.7 kJ/kJ). Furthermore, the global CO_2 emissions was 4.04 kgCO_2equiv./kg ethanol and the CO_2 equivalent index in exergetic base was 149 gCO2/MJ ethanol for the biochemical process. Lastly, this process shows a reduction of 25 % on the CAPEX of the capital investment cost in comparison with the thermochemical pathway.

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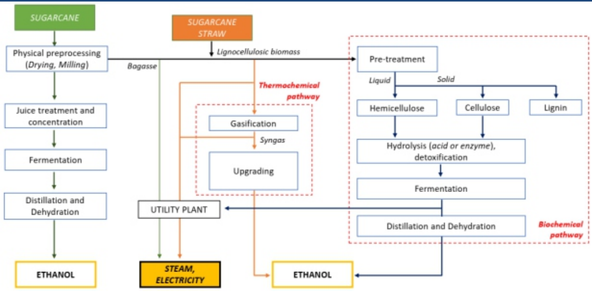
TECHNOLOGICAL PATHWAYS



SPECIFIC OBJECTIVES

- The conceptual design, modeling and assessment of biorefinery systems based on multiple criteria (**e.g.** *energetic, exergetic, economic and environmental*) for sustainable biorefineries configurations;
- Comparing the exergy performances of the technological routes evaluating alternatives to minimize entropy generation (*irreversibility*) in order to improve the quality of the products obtained.
- Identification of opportunities and selection of potential systems for the three selected technological routes based on qualitative comparisons of techno-economic and environmental performance like carbon efficiency, production costs and greenhouse gas (*GHG*) emissions.
- A sensitivity analysis performance to explore the robustness of the designs focusing on the valorization of sugarcane biorefineries for the bioethanol production and electricity generation inside a bio-based economy context.

KEY PERFORMANCE INDICATORS (*KIPs*)

i). Exergy efficiency

$$\eta_B = \frac{\sum \dot{B}_{products}}{\sum \dot{B}_{resources}}$$

ii). Specific CO2 equivalent index *(Exergetic base)*

$$CO_{2\,EE} = \frac{\text{Global } CO_{2\,equivalent\ emissions}}{B_{products}}$$

iv). Irreversibility to exergy (I/Bp) ratio

$$I/Bp_{\ ratio} = \frac{Irreversibility}{\sum \dot{B}_{products}}$$

iii). Irreversibility rate

$$I = \sum B_{inputs} - \sum B_{products}$$

v). Renewability exergy index

$$\lambda = \frac{\sum B_{product}}{B_{fossil} + B_{destroyed} + B_{deactivation} + B_{disposal} + \sum B_{emissions}}$$

$0 \le \lambda < 1$ *environmentally unfavorable*

$\lambda = 1$ *reversible process with non-renewable inputs*

$\lambda > 1$ *environmentally favorable*

$\lambda \to \infty$ *reversible process with renewable inputs*

vi). Average unitary exergy cost (AUEC)

- Exergetic cost is a conservative value accounting for the external exergy that is necessary to render an exergy flow available within a specific productive process.
- The ***AUEC*** is a measure of the cumulative irreversibility and exergy consumption, which occur during the upstream processes to form a given exergy stream.

Exergy Calculation

Exergy chemical (Bch)

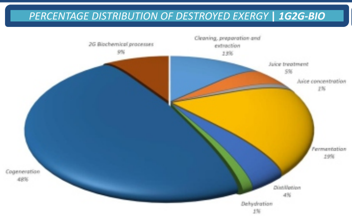
$$B_{ch} = n_{mix}\left[\sum_i x_i b_i^{ch} + R_u T_0 \sum_i x_i \ln \gamma_i x_i\right]$$

Exergy physical (Bph)

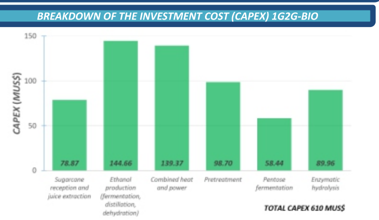
$$B_{ph} = H - H_0 - T_0(S - S_0)$$

BIOCHEMICAL ROUTE

PERCENTAGE DISTRIBUTION OF DESTROYED EXERGY | 1G2G-BIO

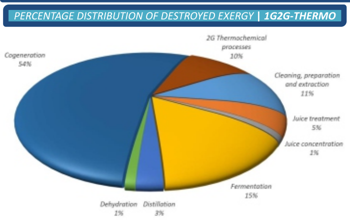


BREAKDOWN OF THE INVESTMENT COST (CAPEX) 1G2G-BIO

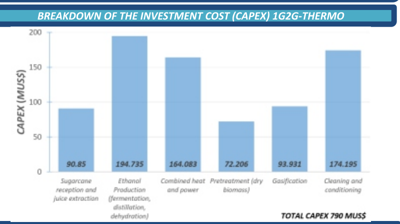


THERMOCHEMICAL ROUTE

PERCENTAGE DISTRIBUTION OF DESTROYED EXERGY | 1G2G-THERMO

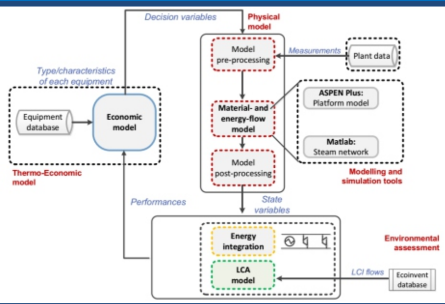


BREAKDOWN OF THE INVESTMENT COST (CAPEX) 1G2G-THERMO



OVERALL PERFORMANCE OF THE BIOREFINERIES CONFIGURATIONS

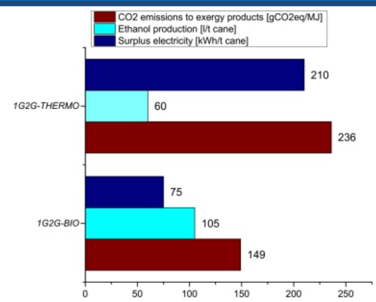
DESIGN OPTIMIZATION METHODOLOGY



TECHNICAL PERFORMANCE INDICATORS - RESULTS

	1G2G-BIO	1G2G-THERMO
PRODUCTS		
Ethanol production *(L/TC)*	105	60
Surplus electricity *(kWh/TC)*	75	210
SYSTEM PERFORMANCE		
System exergy efficiency *(%)*	37	34
I/Bp Ratio *(kW/kW)*	1.42	1.64
Average unitary exergy cost *(kJ/kJ)*	2.7	2.9
DESTROYED EXERGY		
Irreversibility *(MW)*	889	941
ECONOMIC ASSESSMENT		
CAPEX *(US$ million)*	610	790
RENEWABILITY EXERGY INDICATOR		
λ index	0.58	0.76
SPECIFIC CO_2 EQUIVALENT EMISSIONS		
$CO_{2\,EE}$ *(gCO_2/MJ products)*	149	236

KEY POINTS



CONCLUSIONS

- The *KIP's proposed and calculated allowed to determine the global assessment for biorefinery plants producing ethanol and electricity*. The main exergy losses take place in the sub-systems that exhibit the largest irreversibilities, *CHP unit, juice extraction, and ethanol fermentation section*.
- Although this *multi-criteria analysis is applied to the ethanol technology*; it may well-matched for various biorefineries/bioprocesses as a **methodology to support in decision-making as concerns the potential improvement**, well ahead of the detailed process design.
- The techno-economic analysis was performed to assess the 1G2G-BIO and 1G2G-THERMO systems considering the estimation on capital expenditure. ***The global efficiencies shown a better performance in the 1G2G-BIO plant as a function of the processes irreversibility***, highlighting for both pathways the impact of the *destroyed exergy rate* in the CHP unit. Consequently, its dependence on the process performance.
- The exergy-based renewability indicator ***λ*** demonstrated that the sugarcane biorefineries were *categorized as environmentally unfavorable*. However, this **calculation only referred to the industrial processing stage**.

SCIENTIFIC PAPERS

SILVA ORTIZ et al. 2019. *'Exergetic, environmental and economic assessment of sugarcane first-generation biorefineries'.* **Journal of Power Technologies 99 (2) (2019) 67–81. Open Access Journal. ISSN: 2083-4187.**

SILVA ORTIZ P. and MACIEL FILHO, R. *'Compared Comparative performance indexes for ethanol production based on autonomous and annexed sugarcane plants'.* **Chemical Engineering Transactions, Vol. 65, 2018, ISBN 978-88-95608- 62-4.** *DOI:10.3303/CET1865105.*

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