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Techno-economic analysis and exergo-environmental performance of first-generation biorefineries

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Biomass conversion systems have to be developed using advanced technological pathways in order to compete with fossil fuels, as well as to fulfill sustainability criteria. For example, first-generation ethanol (1G) contributes to the majority of the ethanol produced worldwide, predominantly based on corn and sugarcane. Attractive biomass feedstock for ethanol production, which are available in large amounts in several regions. Although 1G is a consolidated process, due to their large-scale production and tradition, there is still room for improved economic and environmental outcomes in the ethanol industry. In addition, several concerns over the long-term sustainability of this technology, such as its intensive water and land use, potential contamination of soils with the distillation residues, along with the competition between food and fuel crops are frequently highlighted.

Accordingly, in this work, a detailed process design strategy for the first-generation ethanol technology from sugarcane were performed using Aspen Plus® software based on the annexed plant-ANX (production of ethanol and sugar) and autonomous distillery- AUT (only ethanol is produced) systems. Hence, the 1G biorefinery process design for ethanol production aiming to develop a thermodynamic-based approach for integrating large resources use efficiency with advanced conversion technologies from a technical, economic and environmental perspective. Consequently, techno-economic and exergo-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, and v). CAPEX (capital expenditure)*.

Results regarding the technical conversion of these systems indicated that the higher exergy efficiency (41%) was presented in the annex process and consequently a lower average unitary exergy cost (AUEC= 2.4 kJ/kJ). Furthermore, the better performance in terms of the global CO_2 equivalent index (exergetic base) was 187 gCO_2/MJ ethanol for the autonomous process. Lastly, the techno-economic analysis was performed to assess the annexed plant (ANX) and the autonomous distillery (AUT) systems considering the estimation of capital expenditure. It is noted that the higher investments are associated with the combined heat and power (CHP), sugarcane reception and ethanol production (juice extraction) sub-systems. For the overall assessment, the results of the economic analysis indicated that the annexed biorefineries processes have the highest CAPEX, 12% the higher capital expenditure, when compared with the autonomous distillery.

The results showed that the annexed plant has a reduction in the process irreversibilities rate of 6 % approximately, and in the average unitary exergy cost rate of 10 % approximately, in comparison to the autonomous distillery. Even though the proposed methodology is applied to the 1G ethanol biorefinery, it may well suited for several biorefineries as a tool to help in taking decisions regarding process design as well as operational policy definitions.

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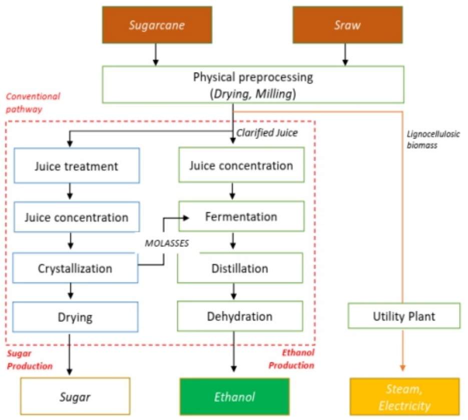
RESEARCH AIMS



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

i). Exergy efficiency

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

***ii). CO_2 equivalent index** (Exergetic base)*

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

iii). Irreversibility rate

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

iv). Irreversibility / Bp Ratio

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

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*

$\lambda > 1$ *environmentally favorable*

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

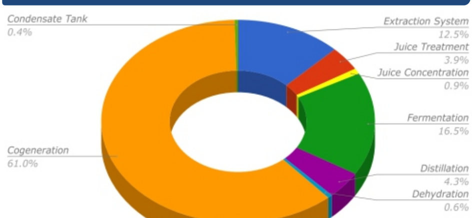
$\lambda \to \infty$ *reversible process with renewable inputs*

vi). Average unitary exergy cost (AUEC)

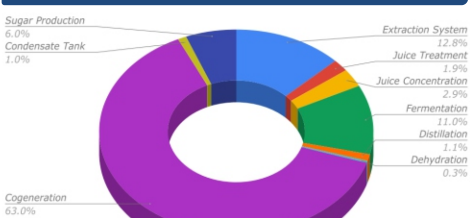
Exergetic cost is a conservative value accounting for the external exergy that is necessary to render an exergy flow available within a specific productive process. The ***AUEC*** is a measure of the cumulative irreversibility and exergy consumption, which occur during the upstream processes in order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

BIOCHEMICAL ROUTE - CONFIGURATIONS OF PROCESSES OF BIOETHANOL PRODUCTION FROM SUGARCANE

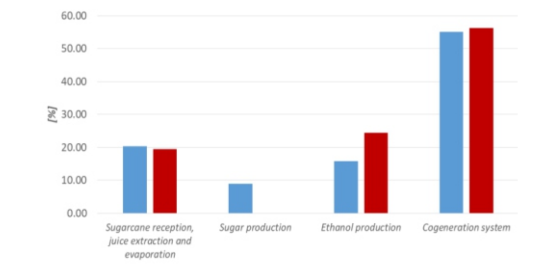
1G-Autonomus plant (1G-AUT)



1G-Annex plant (1G-ANX)

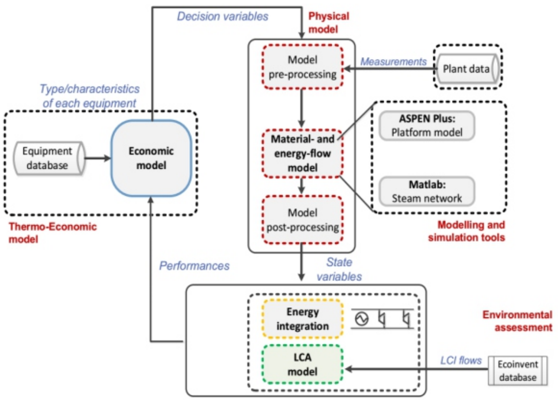


Breakdown of the investment cost (CAPEX) 1G-Autonomous 1G-Annex biorefineries

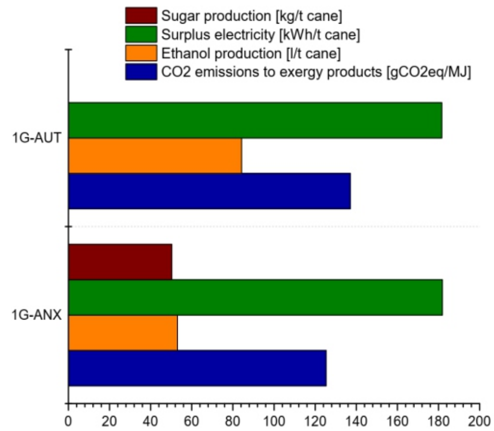


OVERALL PERFORMANCE OF THE BIOREFINERIES CONFIGURATIONS

DESIGN OPTIMIZATION METHODOLOGY



	1G-ANX	1G-AUT
Products		
Ethanol production *[L/TC]*	53.07	84.19
Surplus electricity *[kWh/TC]*	181.86	181.58
Sugar production *[kg/TC]*	50.28	0
System performance		
System energy efficiency *[%]*	48.93	44.81
System exergy efficiency *[%]*	41.39	37.90
Average unitary exergy cost *[kJ/kJ]*	2.41	2.63
Destroyed exergy		
Irreversibility *[MW]*	889	941
Specific destroyed exergy *[kJ/kg$_{biomass}$]*	3460	3666
Economic assessment		
CAPEX *[US$ million]*	345.3	338.6
Ratio I/Bp *[kW/kW]*	1.42	1.64
Specific CO_2 equivalent emissions [gCO_2/MJ product(s)]		
$CO_{2\,EE}$ *(Product: Ethanol, etOH)*	297.17	187.54
$CO_{2\,EE}$ *(Products: etOH + Electricity)*	187.50	137.08
$CO_{2\,EE}$ *(Products: etOH + Sugar + Electricity)*	125.38	137.08



CONCLUSIONS

- The *KIP's proposed and calculated allowed to determine the global assessment for plants producing ethanol, sugar, and electricity*. It must be underlined that the lignocellulosic material in both configurations was consumed in biomass boiler in the cogeneration unit to produce the combined heat and power requirements of the plant whereas exporting the surplus electricity to the grid. This comparison also indicated that the main exergy losses take place in the sub-systems that exhibit the largest irreversibilities, *CHP unit, juice extraction, and ethanol fermentation section*.
- The techno-economic analysis was performed to assess the 1G–ANX plant and 1G-ANX distillery considering the estimation on capital expenditure. *The overall efficiencies shown a better performance in the annexed plant as a function of the destroyed exergy rate*, highlighting for both plants the impact of the irreversibilities in the CHP system and its dependence on the performance of these biomass conversion technologies. Lastly, 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 Technology – Open Access Journal. ISSN: 2083-4187**

SILVA ORTIZ P., 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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