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Methodology for the design and comparison of optimal production configurations of first and first and second generation ethanol with power

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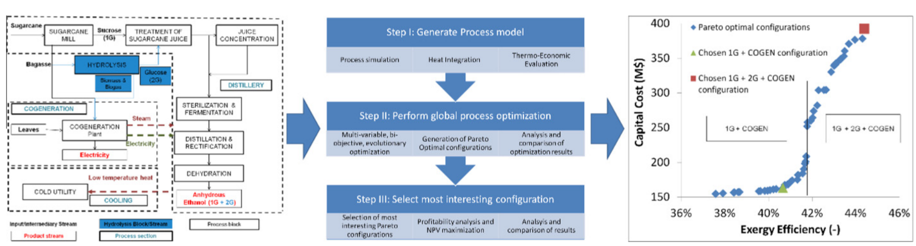
HIGHLIGHTS

- 1st generation (1G) ethanol and power vs. 1G and 2G ethanol and power processes.
- Application of simulation-optimization-selection method for optimal process design.
- Optimization results have efficiencies, costs and utilities better than literature.
- 2G ethanol competitive only for 2G ethanol prices 2–4 times higher than normal.
- Similar design for two processes saves evaporation, utilities, hydrolysis and drying.

GRAPHICAL ABSTRACT



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ABSTRACT

This article applies a systematic methodology to the optimization and comparison of two sugarcane conversion processes of great potential: the production of first generation ethanol and electricity in an integrated distillery and cogeneration plant (1G+COGEN), and the production of first and second generation ethanol and electricity in an integrated distillery, hydrolysis and cogeneration plant (1G+2G+COGEN). The employed method consisted of rigorous process simulation, heat integration, thermo-economic evaluation, bi-objective, exergy efficiency vs. capital cost, optimization and selection via profitability maximization. The exergy efficiency of optimal 1G+COGEN and 1G+2G+COGEN configurations ranged from 37.5% to 41.7% and from 41.8% and 44.42% respectively. Fixed capital increased with exergy efficiency from USD 155 million to USD 209 million and from USD 252 million to USD 393 million respectively. Ethanol production rate averaged at 81.4 L/ton cane (TC) for 1G+COGEN configurations whereas it increased with exergy efficiency to 106 L/TC for 1G+2G+COGEN schemes. Electricity production increased for the first from 122 to 188 kW h/TC and decreased for the second from 180 kW h/TC to 92 kW h/TC. 1G+COGEN schemes presented higher NPV values with a minimum difference of $45 million than 1G+2G+COGEN schemes, with the maximum at an exergy efficiency of 40.65%. Equal profitability was obtained when second generation ethanol selling prices were set at values two to four times greater than the standard, with the most profitable 1G+2G+COGEN configuration having the greater efficiency at 44.4%. A comparison of the two schemes displayed key similarities relating to vapor bleeding, heat integration,

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backward integrated distillation, high boiler pressure and superheating temperature, but also witnessed discrepancies in the evaporators and steam turbines. This work provides a stepping stone in the design of sustainable sugarcane conversion processes, and serves as an example for the efficiency of such methods for the conception of sustainable energy systems.

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Nomenclature

1G+COGEN	first generation ethanol+electricity
ex_{eff}	exergy efficiency (%)
$Ex_{Elec_{net}}$	exergy of net electricity produced (MW)
Ex_{lea}	exergy of leaves (MW)
$\dot{m}_{et}$	ethanol mass flow rate (ton/h)
$Elec_{net}$	net Electricity production (MW)
$\dot{m}_{cane}$	mass flow rate of sugarcane (ton/h)
$\dot{m}_{lea}$	mass flow rate of leaves (t/h)
$\dot{m}_{enz}$	mass flow rate of enzymes (t/h)
C_{Fixed}	fixed capital cost (USD M)
$C_{non\text{-}hex,GR}$	cost of non-heat exchanging equipment (USD M)
MMESP-2G	modified minimum second generation ethanol selling price (USD/L ethanol 2G)
1G+2G+COGEN	first and second generation ethanol with electricity
$Ex_{ethanol}$	exergy of produced ethanol (MW)
Ex_{cane}	exergy of sugarcane (MW)
Ex_{enz}	exergy of enzymes (MW)
ex^0_{et}	specific chemical exergy of ethanol (MW h/t)
ex^0_{cane}	specific chemical exergy of cane (MW h/t)
ex^0_{lea}	specific chemical exergy of leaves (MW h/t)
ex^0_{enz}	specific chemical exergy of enzymes (MW h/t)
$C_{HEN,GR}$	grass root cost of heat exchange network (USD M)
NPV	Net Present Value (USD M)

1. Introduction

The comparison of renewable energy systems has been a key topic in present literature, especially in the case of energy transition [1]. More specifically, the comparison of bioenergy resources and systems has played a central part in this context, namely due to biomass' abundance, its potential to produce multiple energy vectors and the multiplicity of related conversion pathways, which can be integrated [2]. Sugarcane, one of the world's most abundant crops, is a prime example of such a resource. This article considers in this context the comparison of two prominent pathways. The first deals with the production of first generation ethanol along with electricity in an integrated distillery and cogeneration process (1G+COGEN). This involves the production of first and second generation ethanol in a combined distillery, enzymatic hydrolysis and cogeneration plant (1G+2G+COGEN). The technical, economic and environmental comparison of these alternatives was the subject of multiple research works. They thus involved different levels of integration between distillery and hydrolysis plants [3], the use of energy integration and pinch analysis [4], the evaluation of exergy losses per block [5], differing boiler pressures [6], various pre-treatment and hydrolysis methods with different hydrolysis parameters [7,8], the addition of cogeneration and hydrolysis blocks to pre-existing mills [9], different variants of the study processes [10–12], the minimization of costs in the entire fuel chain [13], the use of futuristic hydrolysis and cogeneration technologies, in the South African case [14] and the comparison of greenhouse gas mitigation potential [15]. Furlan et al. [16] and Dias et al. [17] considered flexible units operating at a seasonal basis at full potential for both schemes. Both works indicated that this configuration presented key economic benefits, despite its greater investment cost.

Sensitivity analyses concerning economic parameters such as ethanol and power prices, or capital and enzyme costs, were moreover performed in [3,7,9–13,16,17].

The compared parameters were as follows. The hydrolyzed bagasse fraction and the production rates of ethanol, second generation ethanol and electricity were measured in all works. Therein, bagasse fraction was expressed as a percentage of total produced bagasse or as a mass ratio of input sugarcane. Process steam consumption was measured in [5,8,16,18], energy efficiency in [11,14], investment costs in [8–12,16,17]. Average ethanol production costs were calculated in [8,10]. The minimum selling prices for second generation ethanol (2*G-MESP*) and first and second generation ethanol (1*G*+2*G-MESP*) were calculated in [11,12]. Average electricity production costs were calculated in [8,10,16]. They were greater for 1G+2G+COGEN schemes. The Internal Rate of Return (*IRR*) was evaluated in [8,10–12,16]. Finally, the Net Present Value was evaluated in [16]. Environmental impacts were finally compared with respect to mitigated CO_2 emissions [9,15,17], lifecycle assessments [3,17] and potential for carbon taxing [13].

Key conclusions can be summarized as follows.

Hydrolysis leads to the generation second generation ethanol for smaller electricity production, problematic in the case of grid electricity purchase. Hydrolyzed bagasse fraction depends on all process variables. Steam consumption increases with the inclusion of hydrolysis, due to the greater ethanol production rate. Energy efficiency increases with process improvements, with hydrolysis inclusion leading to greater efficiencies, dependent on the chosen technology. Investment costs were higher for 1G+2G+COGEN configurations, due to hydrolysis, with cogeneration presenting a smaller portion. 1G+COGEN schemes provided better economic results than their 1G+2G+COGEN counterparts, mainly related to their greater investment costs. Other parameters were enzyme costs and the reduction in electricity production. Moreover, greater ethanol prices and smaller capital costs presented the greater potential in increasing the economic appeal of 1G+2G+COGEN schemes, with a higher weight for the first parameter. Moreover, the possibility of exporting second generation ethanol to Europe presented an additional incentive for 1G+2G+COGEN configurations [13]. Finally, environmental performance depended on the chosen technology, reference fuels and power production technologies.

Optimization was also advocated in these works. It the use of heat integration [4], mass integration [11], and the optimization of sugarcane juice concentration [5], ethanol wine purification [10], heat and power cogeneration [6], biomass drying [11] and hydrolysis [7,11] variables. Futuristic hydrolysis technologies also

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