Exergy analysis of the integration of power-to-gas systems to Brazilian sugarcane biorefineries: moving towards maximum energy conversion, minimum waste and zero CO_2 emissions

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As energy production and use account for around two-thirds of the world's greenhouse gases (GHG) emissions [1], renewable energy systems with reduced emissions are needed to both support meeting the emission targets of the Paris Agreement and help reducing climate change effects. In this context, sustainable biomass production plays an important role in climate change mitigation while also providing diversification of energy resources in the long term [2]. Brazilian sugarcane biorefineries have a well-established agricultural production system and processing infrastructure that make sugarcane one of the most advanced feedstocks for bioenergy production [2]. In addition, electricity produced from bagasse corresponds to 11.7% of the final energy consumption and the ethanol corresponds to 16.8% of the liquid fuels used in the transportation sector in the country [3]. However, many improvements are still required to increase the performance of the processes: the energy and carbon conversion should be maximized and carbon dioxide (CO_2) emissions should to be minimized. In typical first generation (1G) Brazilian mills, for example the production of sugar and/or ethanol and electricity, use only approximately two-thirds of the total energy content of sugarcane. The remaining third, present in straw, is left on the field after mechanical harvesting. Moreover, despite contributing to the mitigation of GHG emissions in the road transport sector, 1G sugarcane biorefineries produce approximately 286 kgCO_2 per ton of cane in fermentation and combustion processes [4]. Given the current scenario of sugarcane biorefineries in Brazil and the need for developing sustainable energy systems, the development of sugarcane plants connected to power-to-fuels systems is an opportunity to increase bioenergy production, reduce/neutralize CO_2 emissions and convert by-products into useful and added value fuels and chemicals. Straw, vinasse, filter cake and CO_2, for example, can be converted into ethanol or methanol, fertilizers, biogas and synthetic methane [4, 5]. Furthermore, in future energy systems with a high share of renewable energy is vital for solving the intermittency of inflexible energy sources. In this study, a power-to-gas system integrated to a 1G Brazilian sugarcane biorefinery was analysed based on exergy analysis. Through exergy analysis, it is possible to evaluate the performance of energy conversion processes and identify the process stages with higher potential for improvements [6]. Since the objective of this study is not only maximizing energy conversion in the sugarcane mills, but also reaching lower (or zero, if possible) CO_2 emissions, the CO_2-rich streams were then considered to be used as feedstock to produce synthetic methane via power-to-gas (PtG). The PtG technology here considered uses renewable electricity (i.e. from wind and solar sources) to produce H_2 via water electrolysis, being the H_2 then further reacted with CO_2, in a high temperature methanation process, to form methane. The production of synthetic methane maximizes the carbon utilization yield as the CO_2 that would be emitted to the atmosphere is temporally stored (together with the H_2) in a synthetic fuel. Preliminary results show that the integration of PtG systems to 1G Brazilian sugarcane mills increases, in at least 3 times more, the conversion of the sugarcane carbon into final products (*i.e.*, ethanol, electricity and synthetic natural gas), while reducing the sugarcane carbon conversion into CO_2 from 41% to 3%. Furthermore, the production of synthetic natural gas can reach up to 133.1 Nm^3 per ton of sugarcane, increasing the total mill fuel product per hectare of harvested sugarcane from 9.3 to 33.6 kW per hectare. Concerning the exergy analysis for the 1G plant, the processing stages where exergy destruction occurred were: *i)* cleaning, preparation and extraction (15.3 %); *ii)* juice treatment (5.5 %); *iii)* juice concentration (1.6 %); *iv)* must preparation and fermentation (19.8 %); *v)* distillation (4.4 %); *vi)* dehydration (1.2 %); and *vii)* cogeneration (52.1 %). The results show that fermentation and cogeneration processes are the processing stages with higher destruction of exergy and therefore the ones with better possibilities for further improvement. Consequently, utilization of CO_2 streams from both fermentation and cogeneration processes shall further be considered as relevant options for maximizing both energy and carbon conversion.

Keywords:
Sugarcane biorefineries, Carbon mass balance, Power-to-gas, Global CO_2 emissions, Exergy efficiency, Renewability exergy indicator.

References:
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SUPPLEMENTARY MATERIAL

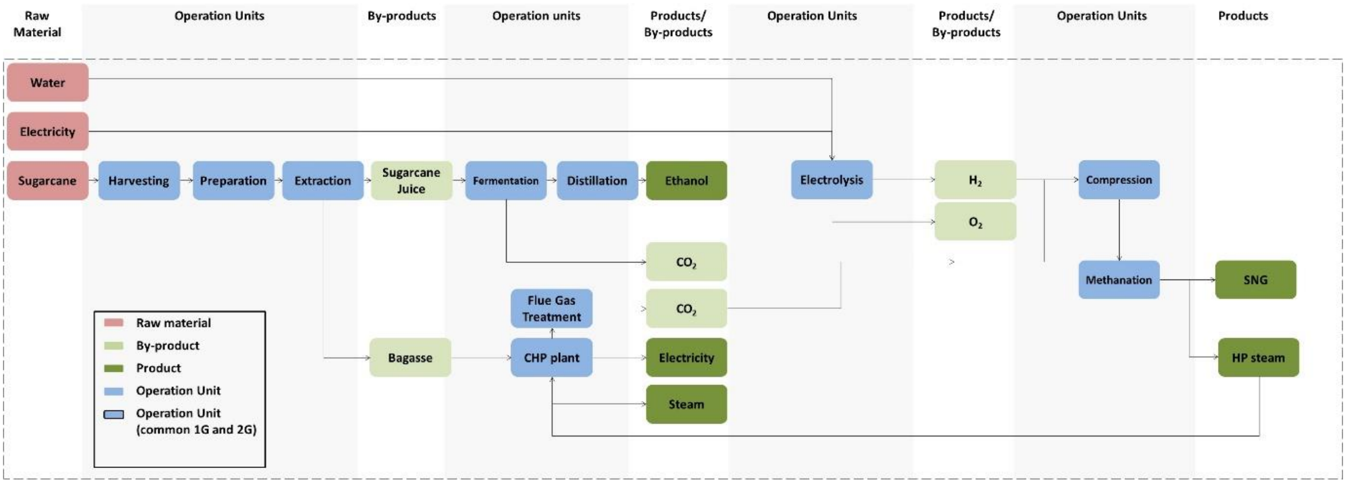

Fig.1 The main process operation units, products and by-products involved the integration of power-to-gas to a 1G sugarcane biorefinery.

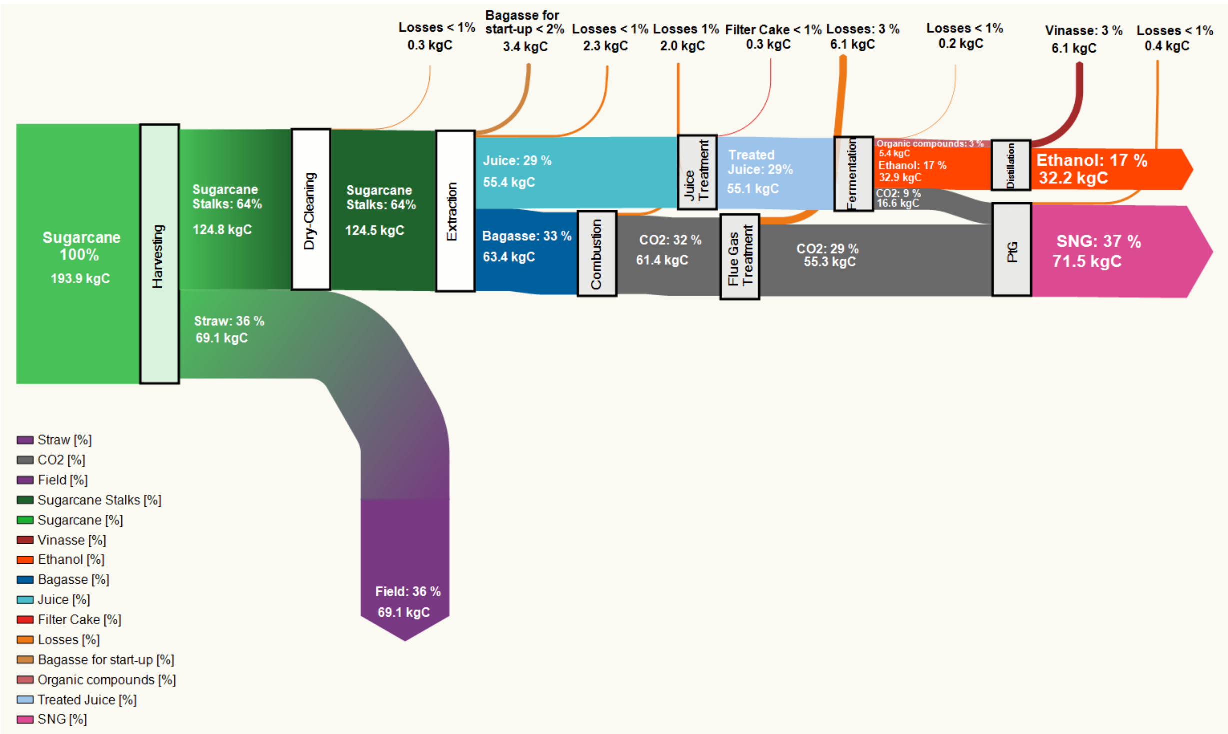

Fig.2 Carbon mass flow rate of the integration of power-to-gas to a 1G sugarcane biorefinery.

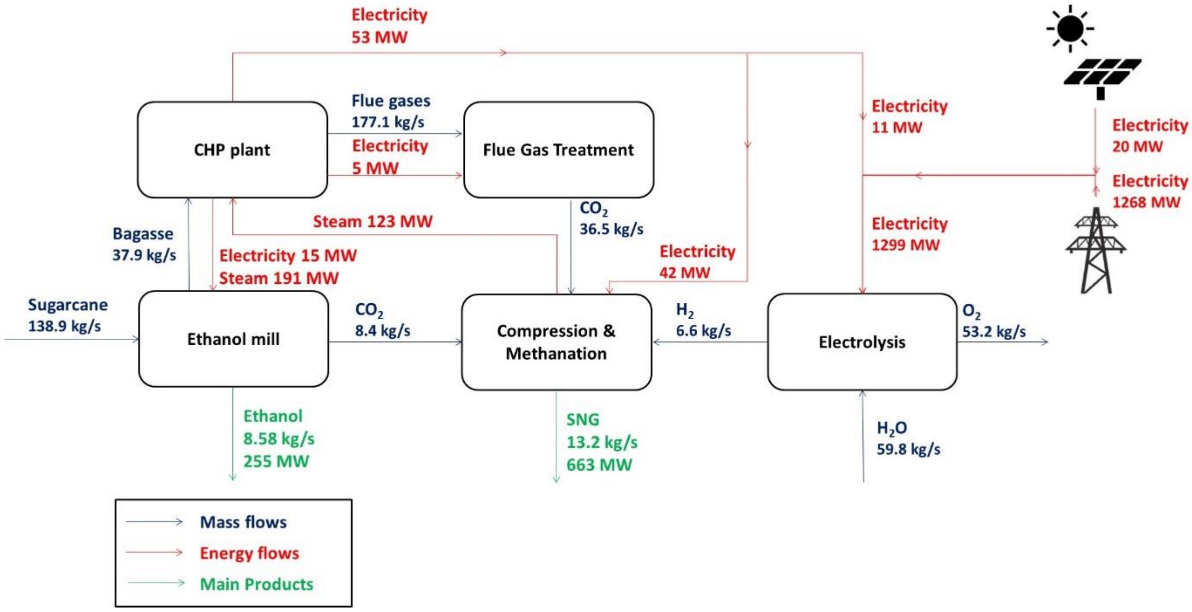

Fig.3 Mass and energy flows of the integration of power-to-gas to a 1G sugarcane biorefinery.