

# Synergies Between the Distillation of First- and Second-Generation Sugarcane Ethanol for Sustainable Biofuel Production

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## ABSTRACT

This work investigated synergies for improved energy efficiency between integrated first- (1G) and second-generation (2G) sugarcane ethanol distillation, an energy-intensive unit operation, especially for stand-alone 2G ethanol. For this investigation, integrated and separated 1G2G distillation simulations were conducted using Aspen Plus v.10 assuming a dilute 2G fermentation beer with titer varying from 5 to 40 g/L. The results were then assessed in heating energy demand savings for distillation, and it was measured the potential of saved bagasse (boiler fuel) for valorization in either electricity or 2G ethanol. A life cycle assessment was also performed for a consequential approach to carbon emission reductions from energy savings. As our main result, distillation integration can maintain the heat demand of a stand-alone 1G mill, regardless of the 2G ethanol beer titer. This means energy savings between 9 and 15% in total ethanol heat demand, and between 46 and 92% in 2G ethanol heat demand. The savings are due to the reflux ratio associated with 2G ethanol distillation becoming close to the host 1G distillation process. However, although the energy savings may result in economic gains, not assessed in this study, by using saved bagasse for either electricity (between 0.14 and 0.23 MJ<sub>Electricity</sub>/kg<sub>Ethanol</sub>) or 2G ethanol production (between 6.8 and 4.1 g<sub>2G Ethanol</sub>/kg<sub>Ethanol</sub>), the boiler fuel savings do not significantly decrease carbon emissions of ethanol production (less than 1%). Nonetheless, the lower energy demand has the potential to debottleneck the operational cost challenge of distillation for 2G ethanol production without associated trade-offs.

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**Keywords:** biorefinery, distillation, sugarcane ethanol, process integration, life cycle assessment

## INTRODUCTION

Achieving a sustainable future requires shifting from non-renewable to renewable energy sources. Among several strategies for energy decarbonization, biofuels are of economic and environmental interest because they produce energy while being carbon-negative if the production process is integrated with carbon capture technologies [1]. Ethanol is one of the most studied biofuels, being produced commercially in Brazil mainly by

fermenting sugars from sugarcane juice (first-generation ethanol) and sugarcane bagasse (second-generation ethanol), resulting in fermentation beer containing mostly ethanol and water.

Among many technologies for ethanol separation, distillation is the traditional choice in industry. However, distillation is also known for being energy-intensive and thermodynamically inefficient [2]. Such energy waste creates unnecessary emissions and costs to the production of ethanol. Although this inefficiency can be

improved by heat integration strategies, such as side heat exchangers and heat pumps [2], first-generation (1G) sugarcane ethanol has already achieved commercial viability in Brazil. Meanwhile, the production scale of second-generation (2G) bagasse ethanol increases yearly with the opening of new mills in Brazil by Raízen [3].

Despite this growth, 2G bagasse ethanol is more energy inefficient than its 1G counterpart because 2G ethanol fermentation beer has lower ethanol titer, increasing heat duty and production costs per ethanol mass produced [4]. This increased production cost can become a limiting factor for 2G bagasse ethanol economic viability in titers below 40 g/L, which is the case of most 2G ethanol fermentation technologies, in stand-alone mills [4]. For this reason and because of the logistics involving transporting sugarcane bagasse, 2G bagasse ethanol is currently commercially produced in plants annexed to 1G ethanol plants, and this configuration can likely become one path of evolution for ethanol production in Brazil.

In the context of 1G2G integrated sugarcane ethanol plants, mixing ethanol fermentation beer from both processes may reduce the production costs of 2G ethanol (personal communication with a 2G ethanol producer). Another approach is to perform an initial stripping of 2G ethanol and then integrate the resulting vapor into a host 1G distillation column. However, the energy advantages of this integrated model compared to its stand-alone counterparts remain unclear. Thus, a preliminary comparison with rigorous simulations is needed to measure the benefits of integrating the distillation of 1G and 2G ethanol from an energy efficiency point of view, as well as the consequences from potential energy savings for the reduction of carbon emissions and residue (boiler fuel) valorization.

## METHODOLOGY

This investigation presents an integrated distillation approach that utilizes a first-generation (1G) distillation column for processing second-generation (2G) ethanol. In this proposed configuration, it is crucial that the rectification section, particularly its condenser duty, remains unaffected by the addition of diluted ethanol.

Whereas the integration can be accomplished through a single-column system that processes beer from both 1G and 2G processes, this work proposes a two-column system, featuring a dedicated column for stripping the 2G beer. The vapor generated in this column is then directed to an integrated column that processes the 1G beer. This dual-column configuration is favored for economic reasons, as it allows for the separation of 1G and 2G bottoms (i.e. stillage), facilitating potential residue valorization through other processes.

This investigation does not compare its findings with other energy-saving distillation strategies, such as

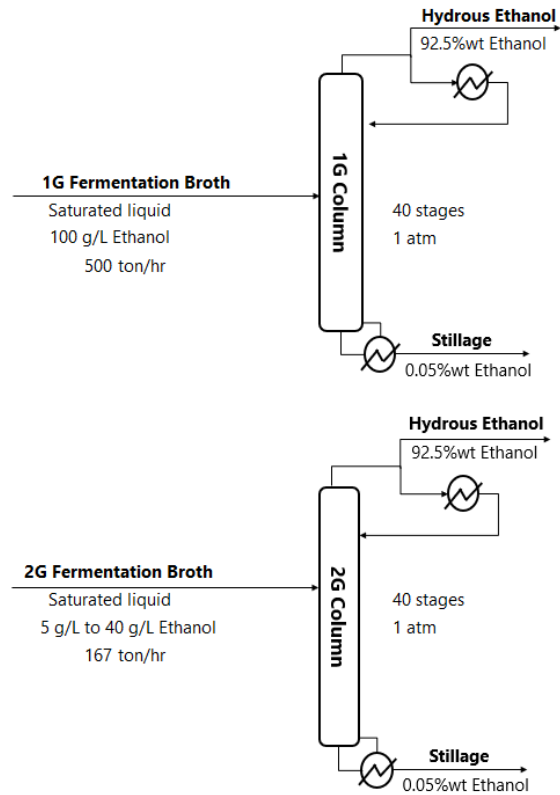
double-effect and heat-pumped distillation. A comprehensive comparison would necessitate an in-depth analysis of the technical, economic, and environmental metrics, given the differing theoretical frameworks of these strategies.

Simulations of separated (Figure 1) and integrated (Figure 2) 1G2G distillation were conducted using Aspen Plus v.10. The nonrandom two-liquid (NRTL) thermodynamic model was used to represent the liquid-vapor equilibrium. The separated distillation configuration comprised two RadFrac columns designed to distill the fermentation beer from both first-generation (1G) and second-generation (2G) processes until reaching near azeotropic levels. In contrast, the integrated distillation setup features an initial column that strips the 2G beer into a vapor phase, followed by an integrated column that distills both the 2G vapor and the 1G fermentation beer until they also reach azeotropic levels. The RadFrac distillation columns were simulated with 40 stages for operation near the minimum reflux condition and to isolate changes in energy demand for only interactions between distillation columns and not due to possible distillation inefficiencies by additional feeds. The RadFrac 2G stripping column was simulated with 20 stages for the same reasons as the distillation columns. In both integrated and separate situations, the final distillate is assumed to be in the vapor phase for the subsequent dehydration step in the ethanol mill. For the purpose of the preliminary analysis reported here, it was assumed that both mixtures enter the columns as saturated liquids, comprising primarily water and ethanol to facilitate a generalized analysis. Additionally, other components, such as residues from the fermentation process, were not included in this assessment. This exclusion is based on the typically low mass fractions of these residues, which can vary depending on the fermentation conditions, and their minimal impact on the overall energy demand of the process.

The distillation system operates at 1 atm, and the 1G beer titer was kept at 100 g/L to represent a typical 1G sugarcane fermentation and the 2G fermentation beer titer was varied from 5 to 40 g/L to study and compare the energy impacts for low titer 2G beer. This analysis assumes that the annexed 2G plant is smaller than the host 1G plant, so it was proposed to use a proportion of 3 kg of 1G to 1 kg of 2G fermentation beer. The mass flow of 1G fermentation beer was assumed to be 500 t/h to be in the same order of magnitude as real ethanol biorefineries [5], but this value will not affect the results because they are measured on a distilled ethanol basis. Additionally, the adopted ethanol mass fraction of distillate was 92.5%wt and of stillage (bottoms) was 0.05% wt to match industrial specifications [5]. Finally, while the proposed distillation system employs a simplified approach, note that there are studies that utilize rigorous simulations of simplified water-ethanol systems specifically for the

energy analysis of distillation [6].

An energy analysis based on the heating energy demand was conducted to quantify and compare the reboilers' duty and distilled ethanol production. In the case of the 1G2G integrated arrangement, the 2G ethanol net duty was considered to be the sum of the 2G rectification column with the heat duty change of the 1G distillation column compared to the separated counterpart.

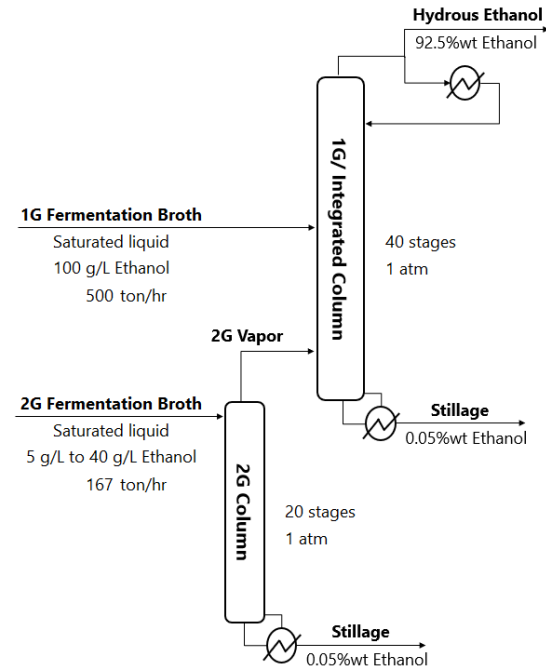


**Figure 1.** Schematic diagram for separated distillation configuration.

The results of the energy analysis were evaluated in terms of biomass demand required to generate the necessary distillation utilities. In other words, the amount of bagasse needed for cogeneration to meet distillation's steam demand. For an accurate estimation, a conversion factor between steam production and bagasse combustion was obtained using the cogeneration spreadsheet model developed for a modern 1G sugarcane ethanol biorefinery boiler system by Bonhivers *et al.* [7].

By estimating the amount of bagasse saved due to energy savings in the distillation, valorization of the saved bagasse was assessed in terms of either electricity production by cogeneration or 2G ethanol production by fermentative route. Whereas electricity production was calculated using a conversion factor obtained from the previously mentioned cogeneration spreadsheet model [7], 2G ethanol production was calculated using a conversion factor between bagasse and 2G ethanol in an

integrated 1G2G sugarcane biorefinery simulated by Bonomi *et al.* [8]. Table 1 contains the conversion factors used in this work.



**Figure 2.** Schematic diagram for integrated distillation configuration.

**Table 1:** Conversion factors to calculate dry bagasse saving and its possible valorization (adapted from [7] and [8]).

Conversion factor	Unit	Value
Bagasse to steam production	MJ <sub>Steam</sub> /kg <sub>Bagasse</sub>	9.97
Saved bagasse to electricity	MJ <sub>Electricity</sub> /kg <sub>Bagasse</sub>	4.12
Saved bagasse to 2G ethanol	kg <sub>2G Ethanol</sub> /kg <sub>Bagasse</sub>	0.12

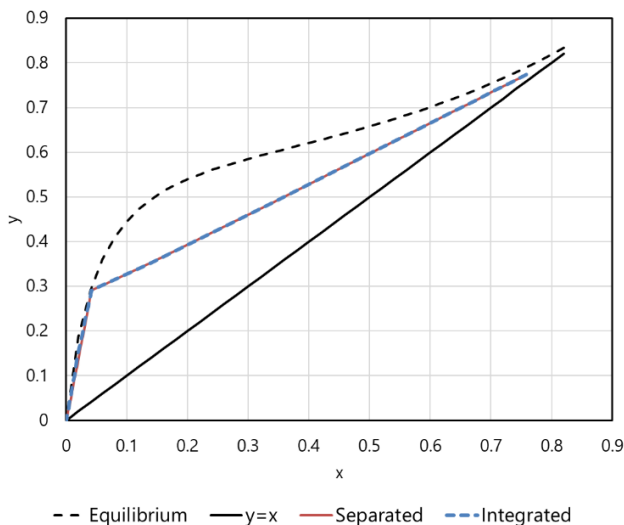
Furthermore, considering the energy savings in distillation, a life cycle assessment was conducted using a consequential approach to evaluate carbon emissions associated with bagasse (boiler fuel) consumption reduction, following the ISO 14040 standard [9]. The adopted system boundary was the boiler and distillation system considering bagasse entering the boiler as an input and distilled ethanol from distillation as output. This system was chosen because it would link steam savings by energy demand reductions in the distillation integration with steam generation by bagasse in the boiler unit. As an observation, the fermentation beers were not considered as input due to not changing in the consequential approach. The functional unit used was 1 kg of distilled ethanol due to ethanol being the product of interest. Multifunctionality was not addressed because there was no

generation of other products. The 2016 ReCiPe Methodology (Hierarchist) was used, the impact category measured was “Climate change”, and it was used the greenhouse gas (GHG) emissions inventory for bagasse for a Brazilian 1G sugarcane boiler by Capaz *et al.* [10].

## RESULTS AND DISCUSSION

From a column operation point of view, distillation integration allows the stripping of 2G beer and the distillation of 1G2G ethanol without efficiency loss when compared with the separated scenario (Figures 3 and 4). Considering a dilute 2G beer feed, the operating lines of the integrated distillation column and the pure 1G column are overlapping, meaning that the reflux ratio does not change. It may be because the 2G ethanol vapor entering the integrated column does not have sufficient mass flow to disrupt the column’s operating line. Therefore, the reflux ratio is comparable to that of a standalone first-generation (1G) distillation system, enabling substantial energy savings in the distillation of second-generation (2G) ethanol, particularly at initial low ethanol concentrations.

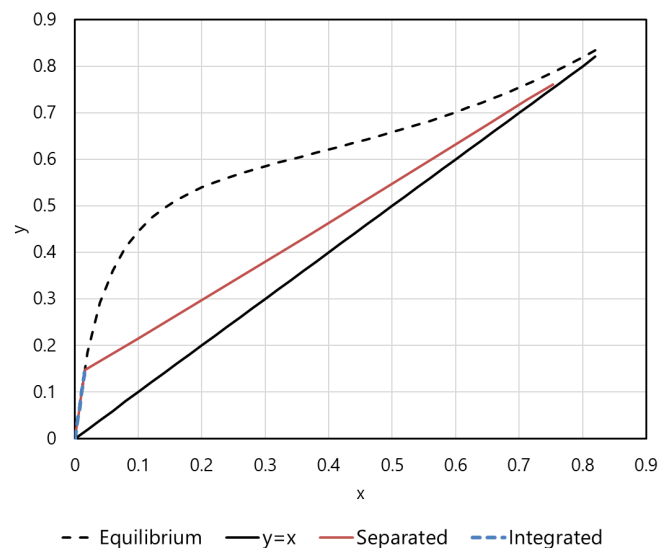
Note that the rectification section of the 2G column does not operate in the integrated scenario. In this configuration, the reboiler duty is primarily linked to the vaporization of the feed, and there is no additional heat requirement associated with the condensing process at the top stage. However, this does not imply that the overall energy demand of the column is significantly reduced compared to a complete distillation process. The stripped vapor has a considerably higher mass flow rate that must be processed, owing to a lower concentration of ethanol.



**Figure 3.** Operating lines for distillation in a stand-alone 1G column (Separated) or an integrated column with 1G fermentation beer and 2G ethanol vapor (Integrated).

Distillation integration is a viable strategy for the energy demand to remain close to a 1G ethanol plant. 1G2G

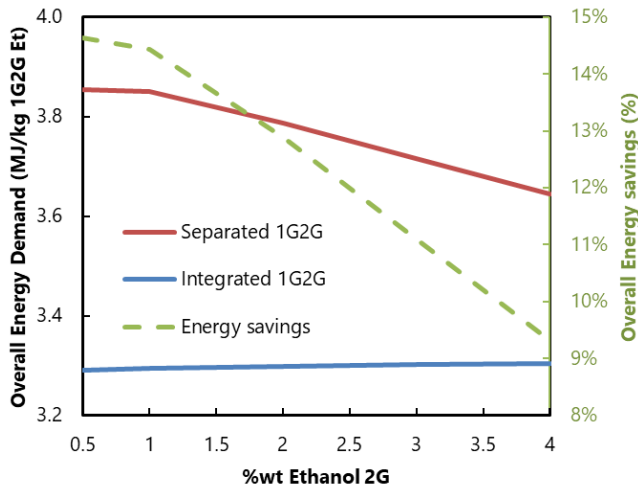
integration resulted in an overall heating energy demand for ethanol distillation at a near-constant value of 3.30 MJ/kg<sub>Ethanol</sub>, regardless of the 2G ethanol titer (Figure 5). Furthermore, the energy demand of the integrated scenario differs by only 0.4% compared to the calculated 1G fermentation beer (3.29 MJ/kg<sub>Ethanol</sub>). Meanwhile, the energy demand of the separated scenario ranges from 3.64 (at 40 g/L 2G beer titer) to 3.85 (at 5 g/L 2G beer titer) MJ/kg<sub>Ethanol</sub>, resulting in energy savings of 9.3% to 14.6%, respectively (Figure 5). The main reason for this result is that the energy demand for distilling 2G ethanol decreases in the integrated 1G2G column due to the reflux ratio being similar to that of a stand-alone 1G system. This alignment with the 1G distillation conditions contributes to enhanced energy efficiency. However, note that the reflux ratio and energy demand of the integrated 1G2G distillation system may vary based on the proportion of 1G to 2G beer and the ethanol titer of the 1G process. This could be observed by a slight increase in energy demand within the integrated system as the ethanol titer rises, specifically around 0.4% when moving from 5 to 40 g/L. This increase is attributed to the higher volume of 2G vapor, which has a subtle impact on the overall operation of the column by increasing the reflux ratio.



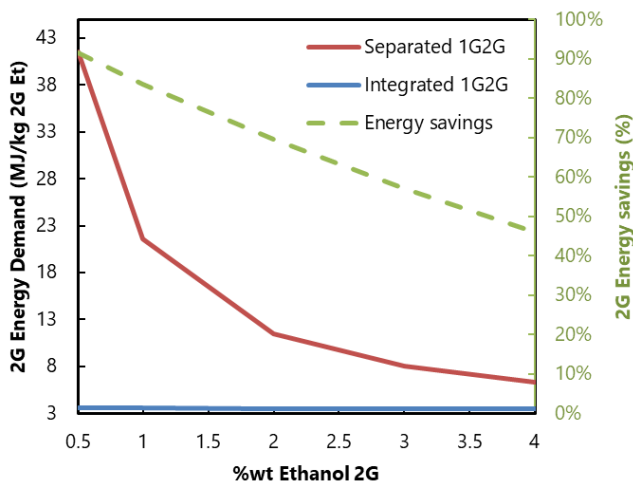
**Figure 4.** Operating lines for distillation in a stand-alone 2G column (Separated) or a 2G stripping-only column (Integrated).

The new reflux ratio condition leads to increased energy savings in the distillation of 2G ethanol. While in the separate scenario, the heat demand varies from 6.34 (at 40 g/L 2G beer titer) to 41.52 (at 5 g/L 2G beer titer) MJ/kg<sub>Ethanol</sub>, the demand is near constant at 3.45 MJ/kg<sub>Ethanol</sub> in the integrated scenario (Figure 6). The corresponding energy savings range from 91.5 to 45.9%, respectively which are significant values in the context of cellulosic ethanol distillation. Additionally, the energy demand

of the integrated scenario is close to the energy demand of 1G ethanol. The relative difference between the integrated 2G ethanol energy demand and 1G ethanol is around 4%, making the operational costs of 2G ethanol distillation close to the stand-alone 1G operation, regardless of the 2G beer titer. Thus, the integration may significantly decrease the typical high distillation operating costs of 2G ethanol production.



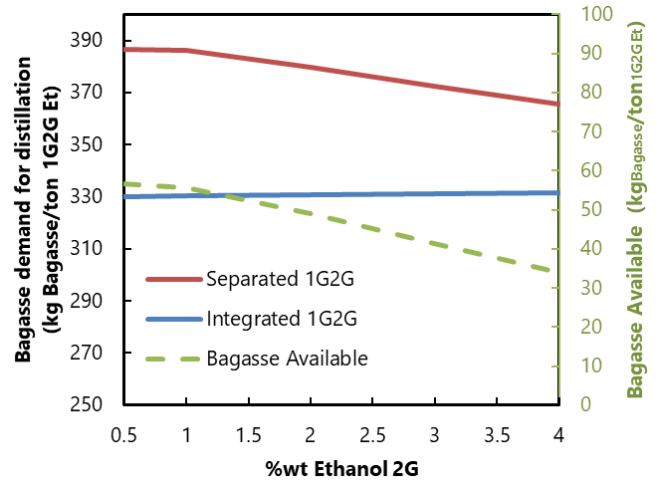
**Figure 5.** Overall energy demand and energy savings comparison between separated and integrated 1G2G distillation.



**Figure 6.** 2G ethanol energy demand and energy savings comparison between separated and integrated 1G2G distillation.

The decrease in energy demand obtained with integration results in savings of bagasse (boiler fuel), which can potentially increase either the electricity or 2G ethanol production (Figure 7). The bagasse savings can vary from 57 (at 5 g/L 2G beer titer) to 34 kg<sub>Bagasse</sub>/ton<sub>Ethanol</sub> (at 40 g/L 2G beer titer) and it could generate 0.23 and 0.14 MJ<sub>Electricity</sub>/kg<sub>Ethanol</sub>, respectively. This electricity production represents an increase of approximately 5% in

electricity output in 1G2G sugarcane ethanol plants, which typically produce 3.29 MJ<sub>Electricity</sub>/kg<sub>Ethanol</sub> [8]. Equally interesting, the bagasse available could produce 6.8 and 4.1 g<sub>2G Ethanol</sub>/kg<sub>Ethanol</sub>.



**Figure 7.** Comparison between bagasse demand for distillation in the separated and integrated 1G2G scenario.

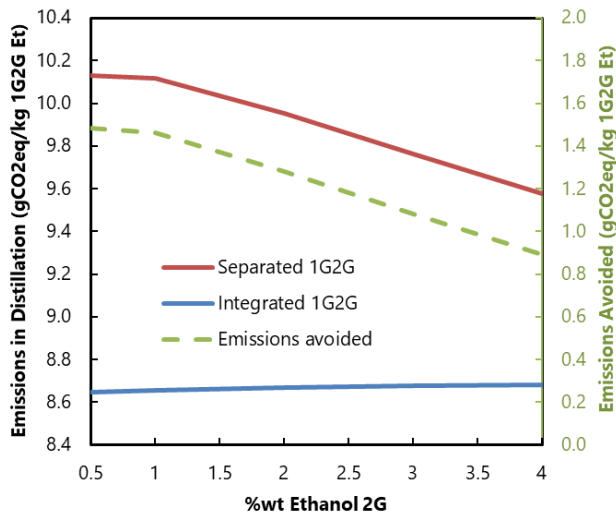
Despite the robust energy savings, the environmental performance is not altered significantly (Figure 8). The corresponding decrease in bagasse demand for cogeneration decreases the GHG emissions by nearly 1 gCO<sub>2eq</sub>/kg<sub>Ethanol</sub>, which is a small amount compared to typical values of sugarcane ethanol production in Brazil [761 (integrated 1G2G ethanol) and 241 gCO<sub>2eq</sub>/kg<sub>Ethanol</sub> (stand-alone 2G ethanol)] [11]. This result was expected because the bagasse used to provide heat for distillation is a renewable fuel and corresponds to a small portion of the environmental profile of sugarcane ethanol production. Nonetheless, in the context of processes with a more energy-intensive distillation that uses fossil fuels such as natural gas in corn ethanol mills in the United States, the energy savings could provide a more significant reduction in the product's emission profile.

## CONCLUSIONS

The integration of distillation processes for first- and second-generation sugarcane ethanol significantly reduces the overall energy demand for distillation, achieving reductions between 10% and 15%. Furthermore, it significantly decreases the heat duty required for distilling second-generation ethanol, with reductions ranging from 47% to 92%. Under the conditions examined, characterized by dilute second-generation feeds, the low concentration of second-generation ethanol led to an integrated distillation setup with both reflux ratio and heat demand closely aligned with the standalone first-generation (1G) conditions, irrespective of the 2G

ethanol titer. Although potential economic benefits may be realized by converting the saved bagasse into electricity or additional ethanol, it is important to note that these energy savings have a limited impact on the carbon emissions associated with sugarcane ethanol production.

Finally, unlike other energy integration strategies such as heat pumps and double-effect distillation, distillation integration offers a straightforward process integration method that achieves energy savings without significant trade-offs.



**Figure 8.** Comparison between greenhouse gas emissions for distillation in the separated and integrated 1G2G scenario.

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