Abstract: Scientific oriented

Topic: 3.1. Biomass integration into energy systems

Integrated appraisal of sugarcane biorefineries for green hydrogen production in the Brazilian case

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Introduction:

While the energy supply in the World was around 11.8% of renewable energy in 2018 (IEA, 2018), the Brazilian primary energy mix of renewable sources achieved 48.4% (139,099 Mtoe) in 2020. Renewable energy mainly consists of sources such as sugar cane products (19.1%), hydroelectric (12.6%), firewood and charcoal (8.9%), wind (1.8%), solar (0.3%), and other renewable sources (5.7%). According to the total electricity supply by energy source, it can be noted that renewable energy contribution was about 85% as shown in Fig. 1, in which hydroelectric, biomass and wind energy sources are the most significant contributors with 65.2%, 9.1%, and 8.8% respectively. Biomass includes firewood, sugarcane bagasse, black-liquor, and other primary energy sources (BEN, 2021).

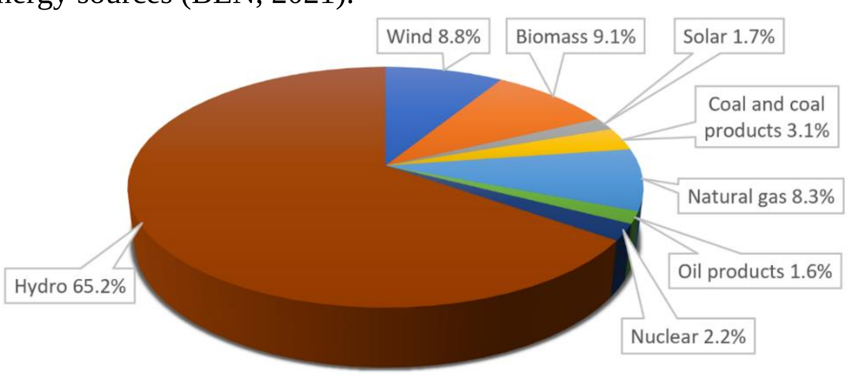

Figure 1. Total electricity supply by source for the Brazilian mix in 2020 (BEN, 2021).

Regarding biomass, 615 units of power plants were installed, totaling a 16.2 GW installed capacity, of which 415 of them use sugarcane bagasse as fuel feedstock (ANEEL, 2022). Thus, the installed capacity of electricity generation by using bagasse biomass was 11.7 GW in 2020, 60% higher than the installed capacity in 2011.

In the world, about 1.8 billion tons of sugarcane are annually produced, and Brazil is the largest global sugarcane producer (Negrão et al., 2021), which is responsible for 38% of global production. It is expected Brazil will continue to be the main producer of sugar and sugarcane-based ethanol in 2028 (FAO, 2019). The industrial processing of sugarcane is usually used to produce electricity, ethanol, and sugar, in which a one ton squeezed sugar cane might produce around 730 kg of sugarcane juice (BEN, 2021). Cavalett et al., (2016) mention that the whole plants contain 7.4 GJ primary energy per ton of cane stalks.

Sugarcane products have a key factor in Brazilian economic development because these not only can be transformed in self-producer power plants for electricity generation or in distilleries for ethanol production but also supply raw materials for the industrial sector such as the food and beverages sector and the paper and pulp sector. In terms of energy consumption of sugarcane by sector, sugarcane bagasse consumption in the energy sector represents about 49.3%, agriculture and livestock demand less than 1% that corresponds with hydrated ethanol used as fuel in agricultural airplanes for agrochemicals and fertilizers application. Moreover, hydrated ethanol (12.7%) and anhydrous ethanol (6.6%) are used to attend to the energy consumption of the highways transportation sector. Finally, the industrial sector's energy consumption is 22.1% (BEN, 2021).

A 6,565 Mtoe (76.4 GWh) energy of sugarcane bagasse produces 38.8 GWh of electricity, accounting for 5.2% of the national electricity generation that is about 621.2 TWh. Most of the sugarcane energy transformation is generated in the Southeast and the Center-west regions of the country with 66.0% and 21.4%, respectively. Furthermore, sugarcane bagasse plants usually operate as combined heat and power (CHP) plants, allowing to increase the energy utilization factor of the power plants. At least a 50% of thermal efficiency is achieved in sugarcane bagasse thermal power plants, which value is higher than conventional power generation plants with fossil fuels.

Sugarcane biorefinery processes:

In Brazil, 72% of the sugarcane biorefineries simultaneously produce both sugar and ethanol products from sugarcane juice (CONAB, 2017), known as annexed distilleries (Morais et al., 2016). Despite both juice treatment routes being similar, each one has its own specificities, for instance, sugar production needs more calcium oxide (CaO) than ethanol production, even a sulphitation process is necessary for white sugar production (Dias et al., 2015).

The sugarcane impurities that become from the harvesting processes are removed from the feedstock in the reception and cleaning steps. Cane preparation guarantees a best performance in the juice extraction. Sugarcane juice extraction usually is developed by using crushing mills. However, diffusers are also being used (Morais et al., 2016). Sugarcane bagasse is employed as fuel in the combined heat and power plants, allowing them to be autoproducers, while more efficient plants can generate electricity surpluses. In 2019, sugarcane biorefineries exported 22.5 TWh of electricity to the grid.

For sugar and ethanol production, the sugarcane juice is physicochemically treated by heating processes and adding chemical components such as phosphoric acid, lime, and flocculant polymer (Dias et al., 2015). Moreover, a thermal deaeration process is carried out for the dissolved air removal. The juice treatment ends with a filtration stage to remove the residue of the juice decantation process, resulting in the filter cake (Rabelo et al., 2015). Finally, multi-effect evaporators are used to concentrate the sugarcane juice, forming the syrup at the outlet of the falling film evaporators.

Sugar production demands subsequent processes such as water removal, crystallization, centrifuging and sugar drying. Vacuum pans allow water removal by using a vessel in which syrup is boiled under vacuum conditions. Thermal damage of the raw sugar can be avoided by using vacuum processes due to lower boiling temperature (Berk, 2018). Sugar crystals along with syrup (or mother liquor), called masscuited, are formed (Baikow, 2013). Crystallizer centrifuging is employed to separate the heavy crystals from the syrup. Molasses is a by-product of the crystallization that can be used with the syrup during the fermentation process.

Ethanol manufacturing processes begin with the broth fermentation (syrup and molasses). In Brazil, the *Saccharomyces cerevisiae* microorganism usually is employed in the fermentation process for ethanol production (Darvishi and Moghaddami, 2019), in which the microorganism limits the ethanol production for ethanol concentrations higher than 11% (v/v) in wine (Darvishi and Moghaddami, 2019) or up to 20% (v/v) (Roukas and Kotzekidou, 2020 - Greece). Thus, a diluted broth is needed to achieve the low ethanol concentration tolerance, demanding higher thermal power in the distillation process (Ponce et al., 2016). The purification process or ethanol dehydration, usually heterogeneous azeotropic distillation with cyclohexane, is carried out to increase the ethanol content, achieving a 99.3 wt% of purity, at least (Dias et al., 2015). It is worth mentioning that hydrous ethanol is commercialized in the market, thus, some kinds of ethanol production plants do not have the ethanol dehydration.

Potential opportunities for green hydrogen production

As it can be noted, basically, sugarcane biorefineries have an enormous potential to be used for green hydrogen potential due to that not only the surplus electricity of sugarcane biorefineries but also the waste products such as bagasse, straw, vinasse, and filter cake can be used for this purpose. However, technical pathways should be studied to estimate that potential, for instance, biogas production by using vinasse and filter cake in the anaerobic digestion processes. Thus, the aim of the current study is the integrated appraisal of sugarcane biorefineries for green hydrogen production in the Brazilian case. Moreover, the proposed routes in the study were defined based on the feasibility of implementation in the current sugarcane biorefineries. The hydrogen production potential considers two main routes; surplus electricity along with electrolysis cells, and the use of biogas productions that become of vinasse for direct biomethane steam reforming, or electrolysis along with internal combustion engine. Results showed that a 0.78 million tons per year of green hydrogen might be produced by using surplus electricity (72.5%) of sugarcane biorefineries and vinasse by-product (27.5%). Finally, the balance of carbon emissions also was considered.

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