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Incorporation of hydrogen production process in a sugar cane industry: Steam reforming of ethanol

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HIGHLIGHTS

- We studied the potential of hydrogen production integration to sugar cane industry.
- We did a thermo-chemical analysis of this production.
- We used an economic method for cost evaluation of hydrogen production integrated to sugar and alcohol industry.

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ABSTRACT

This work presents a technical, ecological and economic analysis of hydrogen production incorporation through ethanol steam reforming at a traditional sugarcane industry (sugar, ethanol). This proposal is reached through a reduction in the amount of fuel (bagasse) that is normally utilized to generate electricity without affecting the sugar and ethanol production processes, however. This surplus bagasse is utilized to produce steam for hydrogen production. In order to achieve this, it is calculated the available bagasse and maximum hydrogen amount and their inputs (hydrated and anhydrous ethanol). Based on the aforementioned, the investment needs are estimated, where the operation and maintenance cost, the operation period, the interest rate, and the annuity are considered. The incorporation of this new process is assessed through a comparison of this innovative plant with the traditional ones.

1. Introduction

The sugar cane industrial sector is one of the main Brazilian economic activities due to its high efficiency and competitiveness [1]. In this segment, sugar mills, alcohol distilleries, and integrated plants of sugar and ethanol are commonly found. In recent years, electricity also has been an aggregate product to this segment, and sugar cane bagasse is being used as fuel in cogeneration systems.

In 2006, there were 300 sugarcane plants in operation in Brazil [2]. A total of 394.4 Mt of sugar cane were processed in the 2005/2006 harvest for the production of sugar and ethanol [3]. In the case of Brazil, the equivalent 1% of its total area (3.6 million hectares) is dedicated to sugar cane culture [4]. This amount provides the production of ethanol at a cost of approximately 0.22 USD/L [4].

In a near future in the hydrogen era, sugar and ethanol mills may be modified to produce hydrogen to be used as fuel, besides the conventional products of the traditional ethanol production chain.

An aggregate production planning model for sugar and alcohol (ethanol) mills was developed by Ref. [5]. The developed mathematical model was based on the process selection model and the lot-sizing production model, and it aimed to help decision makers in production planning, and in the control of several aspects of the process.

A thermodynamic analysis of the ethanol/water system using the Gibbs energy minimization method was carried out by Ref. [6].

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An expanded overview about sugar cane mills where electricity generation is considered as a product to sales was evaluated by Ref. [7], considering thermoeconomic and environmental aspects, and also optimization techniques.

Other production aspects were reviewed, such as a didactic distillation tower developed by Ref. [8], the thermodynamic analysis of electrical power generation control [9], the exergetic analysis of a simplified model for the gasification process based on chemical equilibrium considerations [10], and also an exergetic assessment of the biomass gasification process [11]. In Ref. [12], it was showed that innovative power plant configurations can increase the bagasse-based cogeneration potential.

In Ref. [13], an exergy analysis was run to assess an integrated sugar and ethanol plant with its cogeneration system and, in Ref. [14] strategies, tools and expertise of authors in energy systems optimization were applied to optimize the synthesis and the design parameters of the process, and of the total site starting from the basic idea of dissociating the heat exchanger network design problem from its synthesis problem. A comparative thermoeconomic study of typical systems for sugar cane mills based on real systems that could be adapted to biomass use was presented by Ref. [15].

Simulations of bioethanol production from sugar cane juice and bagasse were carried out by Ref. [16] using software UniSim Design®, where a typical large-scale production plant was considered: 1000 m^3/day of ethanol is produced using sugar cane juice as material. In Ref. [17], simulations of an autonomous distillery were carried out along with utilities demand optimization using Pinch analysis concepts.

Also, the recovery of residues from sugar cane waste for its use as a renewable energy source was obtained, such as [18], and also for educational purposes based on bio-energy [19]. A review of the disposal practices for the agro-industries sugar cane residue, and the trends of energy use in Cuba were carried out by Ref. [20].

In Ref. [21], it was presented a mathematical model for helping mills choose sugar cane varieties for planting which maximizes crop residual biomass energy balance by considering the difference between the generated and the consumed energy in the process of transferring this biomass from the field into the processing center.

Environmental aspects are related [22,23], such as pollutants emission and ecological efficiency that are associated to economic analysis, as it was adapted by Ref. [24,25]. An analysis of the environmental impacts of methanol production from sugar cane bagasse, taking into account the balance of the energy life cycle and its network environmental impacts, both being included in a life cycle assessment approach, was presented by Ref. [26].

Proposed studies on catalysts are very important to steam reforming of ethanol, such as the development of cobalt catalysts to produce hydrogen from ethanol, that was studied by Ref. [27], and it was observed that the ethanol conversion was 50–70% with 10-<1% of CO in the hydrogen.

This work aims to assess the impacts of the incorporation of hydrogen production by ethanol steam reforming in a traditional sugarcane industry. In order to attain this purpose, a thermodynamic, economic and ecological analysis was performed, and a comparison of the traditional and the innovative sugarcane industry is presented. For the economic analysis, the operational cost, the maintenance cost, the operation period, the interest rate, and the annuity factor are considered. The investment to be applied on the reformer is estimated based on Boehm's Technique.

The goal is to make the sugar and ethanol mill production processes more innovative by the incorporation of hydrogen production process through ethanol steam reforming association, as it can be viewed in Fig. 1.

2. Methodology

The methodology adopted in this proposal aims to innovate the production process of sugar and ethanol mills by incorporating the hydrogen production process through ethanol steam reforming.

A technical analysis of the power plant was carried out in order to check the feasibility of electricity reduction and, subsequently, an incorporation of hydrogen production process is considered.

Afterwards, an economic engineering analysis was run in order to allocate production costs of the new proposed configuration, as well as determining the effects on pollutants emission.

Therefore, the incorporation of ethanol steam reforming process into sugar and ethanol mills brings hydrogen production to the sector besides the conventional products (ethanol and sugar), as showed in Fig. 1.

The incorporation of steam reforming process into sugar and ethanol mills consists in a conventional plant for sugar and ethanol production associated to the ethanol steam reforming process. In this context, the produced ethanol which is for the consumer market through the drying process achieves an ideal of purity and alcohol content that is required by the National Petroleum Agency [28].

A fraction of the ethanol produced at the plant is targeted directly to the process of hydrogen production.

After the evaporation of the mixture of ethanol and distilled water, there are two catalytic steps: one occurring at high temperatures in a device named reformer in which the steam reforming reactions (SRR) occur, and the other one occurring at lower temperatures in a reactor, called as the shift reactor, in which water–gas shift reactions (WGSR) occur.

2.1. Ethanol steam reforming

In the global reaction of hydrogen production utilizing ethanol, 6 mol of hydrogen from 1 mol of ethanol are produced.

The global reaction is shown in Eq. (1). At high temperatures, this one consists in a reaction of ethanol and water in a gaseous state, resulting in the production of carbon dioxide and hydrogen, as shown by Ref. [29].

$$C_2H_5OH_{(v)} + 3H_2O_{(v)} \rightarrow 2CO_{2(g)} + 6H_{2(g)} \quad (1)$$

Eq. (2) shows the steam reforming reaction which is an endothermic reaction of ethanol with water, resulting in the production of carbon monoxide and hydrogen. This reaction may occur through an external reforming process.

$$C_2H_5OH_{(v)} + H_2O_{(v)} \rightarrow 2CO_{(g)} + 4H_{2(g)} \quad (2)$$

The water gas shift reaction is exothermic and reversible, that can occur at lower temperatures than the latter reaction. However, the CO conversion is incomplete, and an additional process to remove it is necessary, as shown in Eq. (3).

$$CO_{(g)} + H_2O_{(v)} \rightarrow CO_{2(g)} + H_{2(g)} \quad (3)$$

Several chemical reactions can occur simultaneously with the steam reforming of ethanol reaction. Eq. (4) shows a representative equation, that is, a production of methane from carbon monoxide, also called as methanation.

$$CO_{(g)} + 3H_{2(g)} \rightarrow CH_{4(g)} + H_2O_{(g)} \quad (4)$$

In Bouduard's reaction, the production of carbon is described through carbon monoxide decomposition, as shown in Eq. (5).