

Chapter 18

Technological Advancements in Biohydrogen Production and Bagasse Gasification Process in the Sugarcane Industry with Regard to Brazilian Conditions

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Abstract Global warming is caused mainly by the excessive use of fossil fuels (coal, oil, diesel, gasoline, etc.) that emit millions of tons of pollutants into the environment. Besides, the fact that these fossil fuels are nonrenewable resources promotes the research in cleaner energy sources. In this chapter are presented two different technologies that could be introduced in the sugarcane industry to generate electricity and other kinds of clean fuel (producer gas and hydrogen); the case of hydrogen production by ethanol steam reforming and biomass gasification, which appear like promising technologies for energy generation in the sugarcane

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industry. Currently, most hydrogen is obtained from natural gas through a process known as reforming. Other technologic alternatives that may improve the supply of energy to the sugarcane industry is the use of biomass gasifiers in association with cogeneration system utilizing combined cycles to produce simultaneously electricity and heat, a technology known as Biomass Integrated Gasification/Gas Turbine Combined Cycle (BIG/GTCC). Cogeneration, has been accepted by different industries and has gained great application in the sugarcane industry, where the thermic and electric demands are favorable to use this type of energy system. The main fuel used in the process is sugarcane bagasse which is a by-product of sugar and ethanol production processes; the obtained energy is used in the form of mechanical power, electric power, and saturated steam in the processes. The surplus electricity can be sold. Technical, economical, and ecological analyses were performed for introduction of hydrogen production and BIG/GTCC in the sugarcane industry, using bagasse as fuel, in order to identify the better scenarios for electricity and heat generation. The introduction of these technologies will engender innovations in the sugarcane industry and will promote the sector development and as main results will increase electricity production with an economic and ecologic sustainable approach.

18.1 Introduction

The gradual increase in energy demand and environmental pollution caused by combustion processes of fossil fuels, has made necessary the development of new technologies employing alternative fuels, thus facilitating the reduction of dependence on fossil fuels oil, natural gas, and coal. Generally, the combustion process of fossil fuels produce greenhouse gases such as CO_2 , NO_x , and others that increases the temperature. Energy consumption, mainly in developed countries, has reached incredible limits, which has led, combined with other factors, the increase in global warming, with large worldwide implications. Biomass is a renewable resource that plays a substantial role in the sustainable energy future. Currently, the sensitivities to environmental issues and energy security have led to the promotion of the use of endogenous renewable energy sources. Biomass as an energy source covers 10 % (50 EJ) of the global primary energy source (IEA 2009). Sugarcane is cultivated in more than 80 countries and the by-products obtained from the sugar production process represent a great biomass potential. The harvest of sugarcane in the producing countries is about 1.2 Gt and potentially its residue can be used for electric power production of 300 TW h y^{-1} (Filippis et al. 2004). Besides, nearly 95 % of hydrogen is produced from fossil-based materials, with steam reforming of methane being the most used and usually the most economical option. However, in this process, carbon is transformed into CO_2 and released into the atmosphere, leading

to global climate change (Navarro et al. 2005); thus the main interest is focusing on alternative methods for the production of hydrogen from renewable energy sources. These processes are being investigated as long-term solutions, while generation of hydrogen from biomass has been recognized as a more feasible option for the near-term solution due to its renewable and carbon-neutral nature (Yang et al. 2006). In this chapter are presented two different technologies that could be introduced in the sugarcane industry to generate electricity and other kind of clean fuel (producer gas and hydrogen); specifically hydrogen production by ethanol steam reforming and biomass gasification, which are promising technologies for energy generation in the sugarcane industry.

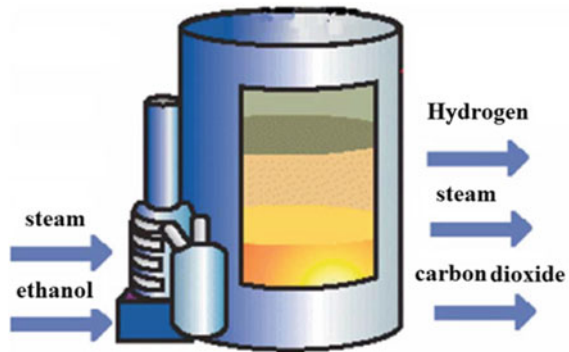
18.2 Incorporation of Biohydrogen Production in Sugarcane Industry

Fuel Cell (FC) appears like a promising alternative technology for energy generation, since it is any efficient system that consists of an electrochemistry process. In this process, water, electricity, and heat are generated through the combination of hydrogen and oxygen (Silveira et al. 2009). Hydrogen can be produced from a variety of sources including water and biomass (Silveira et al. 2008). Currently, most hydrogen is made from natural gas through a process known as reforming.

18.2.1 *The Steam Reforming Process*

For hydrogen production, several technologies can be used. Steam reforming is one of the most common installed in chemical industries. The reforming process efficiency is a function of physical–chemical properties of feedstock, thermodynamic conditions (temperature and pressure of reaction), technical configurations of reformer (dimensions and catalysts), and feedstock and water flows. The reformer to be used depends on the fuel cell, which will use the reforming products. The fuel cell technology determines the hydrogen purity required. Steam reforming occurs in the presence of a catalyst, the syngas produced includes hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), among others. Some arrangements to minimize various reactions that can contribute to decrease the hydrogen production are necessary. Since this reaction is endothermic, heat from external sources is necessary. To minimize losses, several products of steam reforming, like the nonreacted fraction of reactants, might be utilized to heat up the reactants (Souza et al. 2006).

Fig. 18.1 Inlet and outlet flows of ethanol steam reforming process (Silveira et al. 2009)



18.2.1.1 Ethanol Reforming Reactions

Souza et al. (2006) indicated that this way of reforming can be described through the following main reactions:

- *Global reaction.* Ethanol reacts with steam in an endothermic reaction, taking place in the production of carbon dioxide and hydrogen, as shown in Eq. 18.1:

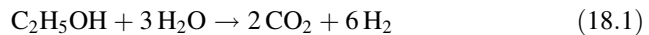
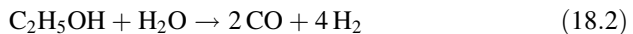


Figure 18.1 shows inlet and outlet flows of ethanol steam reforming process, and Fig. 18.2 shows the prototype developed in São Paulo State University, by Energetic Systems Optimization Group (www.feg.unesp.br/gose).

- *Ethanol steam reforming reaction.* Equation 18.2 shows the reaction where the production of carbon monoxide and hydrogen occurs:



- *Water Gas Shift Reaction.* Since carbon monoxide damages fuel cell catalyst, an additional process is necessary to remove it. The Water Gas Shift Reaction (Eq. 18.3), is exothermic, reversible, and occurs at lower temperatures than the forming reaction:



- *Methanation.* Several chemical reactions occur simultaneously. Equation 18.4 shows methane production from carbon monoxide:



- *Bouduard Reaction.* This reaction (Eq. 18.5) describes carbon production from carbon monoxide decomposition:





Fig. 18.2 Prototype developed in São Paulo State University

18.2.1.2 Hydrogen Production in Sugarcane Industry

Brazil has the largest and most successful biofuel programs in the world, involving production of ethanol from sugarcane and has the world's first sustainable biofuel economy. Together, Brazil and the United States lead the industrial world in global ethanol production, accounting for 70 % of the world's production (Silveira et al. 2009). The Brazilian sugarcane-based industry is far more efficient than the corn-based industry of USA. In the near future, the sugarcane industry of Brazil could be modified according to our purpose, as shown in Fig. 18.3. In this case, in addition to the production of sugar and ethanol, the Brazilian sugarcane industry will be able to produce biohydrogen.

The goal is innovation in the sugarcane industry production chain through incorporation of hydrogen production process by steam reforming of ethanol.

It is proposed to incorporate ethanol steam reforming to the traditional sugarcane industry process which is composed of extraction, juice treatment, evaporation, cooking, fermentation, and distillation to produce ethanol and sugar as well as electricity generation through cogeneration system, as shown on Fig. 18.3. These processes are described below:

- *Extraction.* In this step the cane is cleaned and milled. The milling consists in breaking the hard structure of the cane and grinding it. To increase the amount of juice, water is added. The bagasse obtained from extraction is used in the boiler of the cogeneration system, as shown in Fig. 18.4 (Pellegrine 2009).

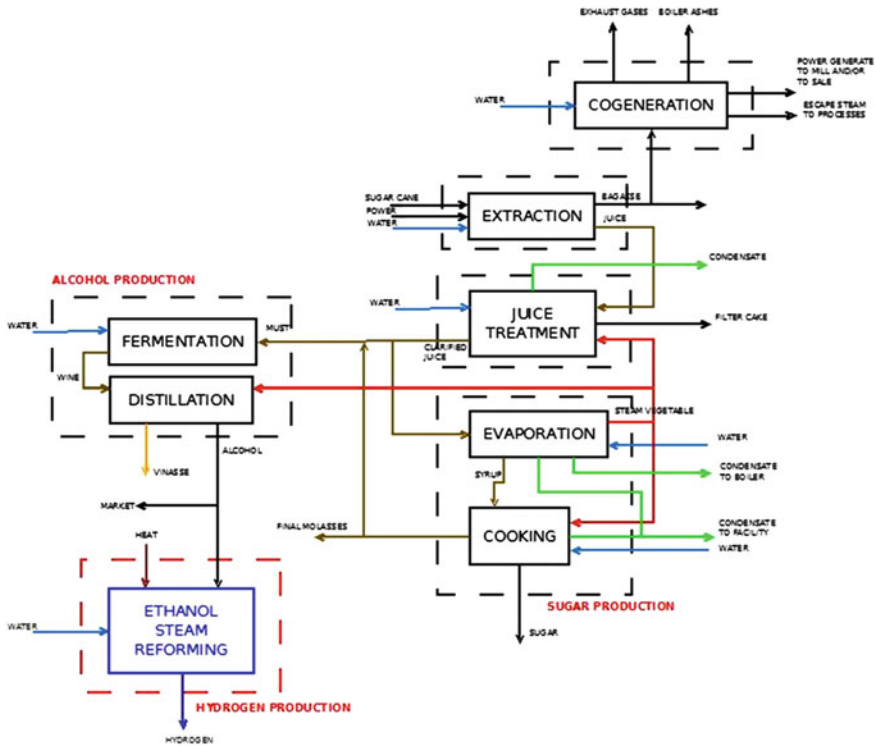


Fig. 18.3 Incorporation of steam reforming process to sugarcane industry

- Juice treatment.** The juice is first strained to remove large particles. Then it is treated with chemical substances to modify the pH, coagulate the colloidal material (greases, proteins, etc.), and precipitate certain impurities (organic acids, sulfates, etc.). The purification process is chosen according to the sugar type that is desired to produce. After the addition of chemical substances, the mixture is heated with water vapor in high pressure. The insoluble particulate mass (mud) is separated by decantation (Silva 2010). Clarified juice goes to the evaporators without additional treatment. The mud is filtered and the filter cake is washed with water.
- Sugar production.** According to Castro (2001) the sugar production involves two steps: evaporation and cooking, as described below.
- Evaporation.** In this step the clarified juice is concentrated. First the juice is passed through heat exchangers to preheat and then to the evaporator stations, typically a series of five evaporators called multiple-effect evaporators. The concentrated juice (syrup) follows to the cooking step (Silva 2010).
- Cooking.** The syrup goes through the second phase of concentration until it takes the consistency of honey and begins to form sugar crystals. Once crystallization is complete, the massecuite is centrifuged and the crystallized sugar and honey

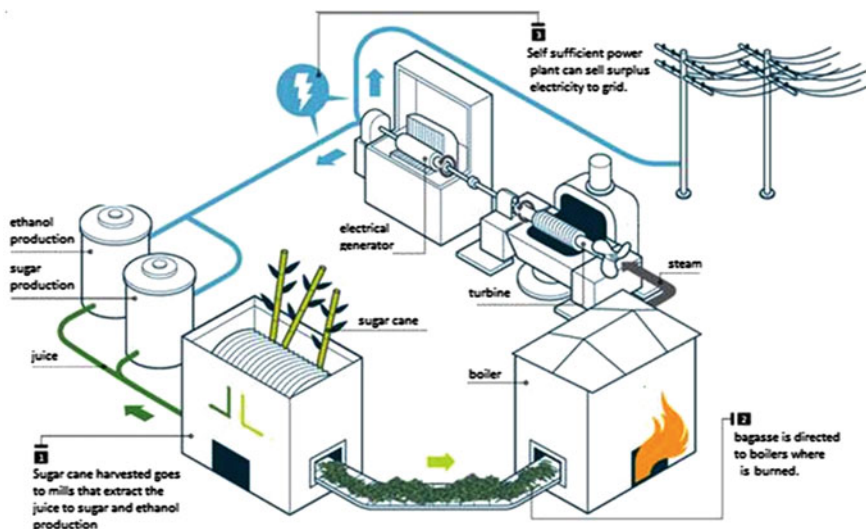


Fig. 18.4 Cogeneration system (Bernardo 2013)

are separated. The crystals obtained are of good quality and the syrup returns to the crystallization process. The end honey, or molasses, can be used as raw material for the fermentation of ethanol. The crystal sugar obtained goes through the refining process, where it is transformed into amorphous sugar, aiming to improve the purification and composition (Silva 2010).

Pellegrine (2009) advocates two stages for alcohol obtaining: fermentation and distillation.

- *Fermentation.* The mud is diluted to correct the concentration and transferred to vats where the fermentation process takes place. In this stage are added nutrients, antiseptic, and yeast, mainly responsible for fermentation. After that, wine is obtained, which goes to the distillation process (Pellegrine 2009).
- *Distillation.* The wine is directed to a decanter and after that to centrifuge where the yeast wine is obtained. It is transferred to a wine reservoir where the alcohol is separated through distillation processes (Silva 2010).

The cogeneration system is shown in Fig. 18.4.

In 18.4, after juice extraction, bagasse is directed to the boilers where it is burned. The steam from boiler goes to the steam turbine, which is connected to the electricity generator. In self-sufficient power plants, the surplus electricity can be sold to grid. As a result of the incorporation and the new configuration of the sugarcane industry will be produced hydrogen in addition to sugar, ethanol, and electricity.

18.3 Incorporation of Biomass Gasification in Sugarcane Industry

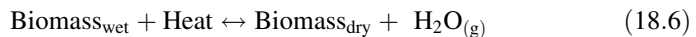
Traditionally, sugar mills use bagasse and cane trash with high moisture content as fuel for low pressure boilers to generate steam, using a conventional condensing–extraction steam-turbine (CEST) technology to provide the plant with heat, electricity, and mechanical power. The recent years have seen more modern systems for burning bagasse in suspension that allow to raise the steam pressure and temperature for the purpose of obtaining a higher electric power cycle cogeneration. The plant thermal efficiency is usually in the 15–30 % range, consequently the size of conventional combined heat and power generation plants from bagasse have been limited by these low efficiencies and the amount of fuel within an economical transportation radius.

The BIG/GTCC technology has been identified by several authors (Babu 1995; Larson et al. 2001) as an advanced technology with the potential to be cost-competitive with CEST technology using the biomass by-products of sugarcane processing as fuel, while dramatically increasing the electricity generated per unit of sugarcane processed. This type of technology does not require a large investment demand and can be inserted into the production process of ethanol (Sánchez Prieto and Nebra 2001).

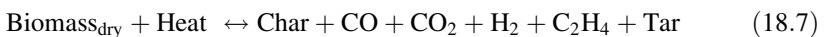
18.3.1 Biomass Gasification Process

Gasification is a thermochemical process in which a carbonaceous substrate is transformed into a fuel gas, through a number of reactions that take place at high temperature in the presence of a gasifying agent (air, oxygen, and/or water vapor). The gasification process includes the following steps:

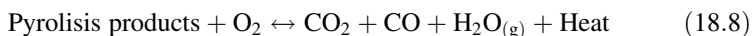
- *Drying* is an endothermic process and to achieve acceptable efficiencies the maximum amount of moisture in the solid is limited between 20 and 30 % by weight. The drying process begins at temperatures below 100 °C and can be expressed by the following reaction:



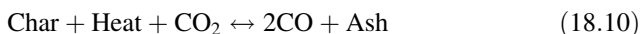
- *Pyrolysis* is an endothermic process, consists of biomass thermal degradation, and is developed at temperatures between 200 and 600 °C. The pyrolysis products are carbon, condensable gases (light and heavy hydrocarbons), and noncondensable gases (methane, water vapor, carbon monoxide, hydrogen, and carbon dioxide). The reaction can be represented as



- *Oxidation.* The oxidation step is important from the energy point of view, since it is the exothermic reaction that releases the energy required to develop the gasification process. The reaction represented by this phase would be:



- *Reduction.* The reduction step begins to develop significantly when the solid reaches a temperature around 700 °C. Thus, the char reacts with water vapor, carbon dioxide, and hydrogen, and gases react together to produce the final gas mixture, obtained as a result of the following reactions:



The producer gas is the principal product of gasification, and its lower heating value (LHV) varies depending on the composition of biomass and the gasifying agent employed. Using air as the gasifying agent, the LHV of the producer gas is in the range between 4 and 6 MJ/Nm³ and using water vapor or oxygen the LHV is between 8 and 20 MJ/Nm³ (Reed et al. 2005).

18.3.2 Gasification in Fluidized Bed Reactors

Fluidized bed reactors are those in which the gasifying agent circulates inside them at a rate such that a bed is in a state of fluidization, existing inside the gasifier several conditions that intensify the transfer of energy and material between the fuel and gas. There are two main categories within these types of gasifiers: bubbling and circulating. In the bubbling fluidized beds, the fluidizing velocity–gasifying agent is sufficiently low as there is no significant movement of solid. By contrast, in the circulating fluidized bed, the velocity of the agent is much higher resulting in a solids circulation. This solid is recirculated to the reactor by the use of a cyclone return system to the gasifier. The main advantages of fluidized beds include better control of temperature and reaction rates, high specific capacity, potential scaling to larger sizes, and adaptation to changes of biomass. On the contrary, show moderate–high tars and particulates levels in the exhaust gas and the fuel conversion are not as high as in the fixed bed gasifiers. A comparison between bubbling and circulating fluidized bed gasifiers is shown in Table 18.1 (Williams et al. 1995).

Table 18.1 Comparison between bubbling and circulating fluidized bed gasifiers

Fluidized bed reactor	Temperature (°C)		Biomass	Feed	Gasification agent	Tar content
	Reaction	Exit				
Bubbling	700–1000	700–800	Wood chips, leftover corn cobs, rice husks	Directly in the area of the bed	The bottom of the gasifier	Medium–High
Circulating	700–1000	600–800	Sugarcane bagasse, wood chips, sawdust, rice hulls	Directly in the area of the bed	The bottom of the gasifier	Low

18.3.3 Biomass Gasification Technology for Cogeneration of Heat and Power

Cogeneration study can be divided into three different types of cycles. The conventional cycle in which steam is used at low pressure and temperature and the steam and power generated is just enough for own consumption of the plant. A second cycle is the advanced cycle with similar configuration to conventional cycle but operating with a higher pressure and temperature, which results in significantly greater generation of electricity than the needs of the sugar factory; the excess energy can be sold to external consumers. The third cycle is the BIG/GTCC and also generates an excess of electricity. The combined cycle system is the simplest scheme used for cogeneration, shown in Fig. 18.5. It employs a gas turbine, a heat recovery steam generator without supplementary firing, and steam-turbine (Silveira et al. 2006).

18.3.4 Sugarcane Bagasse as Biomass

There are several studies on the use of sugarcane bagasse as fuel in gasification processes. Olivares (1995) studied different types of bagasse with the objective of introducing it as fuel in a fluidized bed gasifier. Bagasse is a material with high fiber content and low density and has an extensive range of sizes. It exits the sugar production process with a moisture content of approximately 50 % (wet basis); for this reason, a pre-treatment process is necessary that includes drying, crushing, and others in order to improve their properties and facilitate the feeding process to fluidized bed reactors.

One of the principal parameters to evaluate the quality of bagasse is the moisture content because the more humid bagasse will decrease its lower calorific value (LHV), and therefore it will have less available energy for the same amount of fuel.

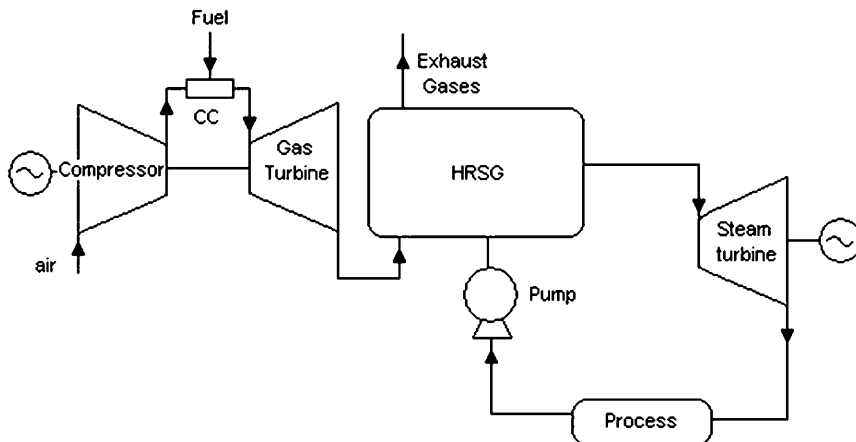


Fig. 18.5 Gas turbine associated with the steam turbine (Combined Cycle)

Table 18.2 shows the main physical and chemical properties of sugarcane bagasse reported by Jenkins et al. (1998). Bagasse is classified as a fuel with high reactivity due to its high content of volatiles and low ash content, making it a good feedstock for gasification.

18.3.5 Combined Cycle Associated with a Fluidized Bed Gasifier

In a combined cycle, the fuel combustion provides the mechanical energy to the electric generator and the exit gases from the combustion are directed to a heat recovery steam generator to produce steam; this steam will drive a steam turbine that will be linked the other electricity generator. It is generally employed in this type of cycle-to-cycle Brayton combination with a Rankine cycle type (Diniz et al. 2013). To have the possibility of entering the gasifier in this cycle, there must be previous drying since the sugarcane bagasse has relative humidity around 50 % *in natura* (Olivares et al. 1995). It is also necessary to clean the producer gas generated, since it contains a load of particulate and tar, as shown in Fig. 18.6.

Research has shown the potential of BIG/GTCC-based systems to be competitive with, if not superior to, conventional combustion power plants because of their higher efficiency, superior environmental performance, and competitive cost (Reed et al. 2005). However, much of the advancements are still under research and development. BIG/GTCC is a combination of two leading technologies: gasification and gas turbine combined cycle. The gasification portion of the BIG/GTCC plant produces a clean gas which fuels the gas turbine. For this system, the gasification stage is carried out in a fluidized bed. Typical operating temperature of

Table 18.2 Main physical and chemical properties of sugarcane bagasse (Jenkins et al. 1998)

<i>Proximate analysis</i>	
Volatile matter (wt%, dry basis)	85.61
Fixed carbon (wt%, dry basis)	11.95
Ash (wt%, dry basis)	2.44
Higher heating value (MJ. kg ⁻¹ , dry basis)	18.99
<i>Ultimate analysis (wt%, dry basis)</i>	
C	48.65
H	5.87
O (by difference)	42.82
N	0.16
S	0.04
Cl	0.03

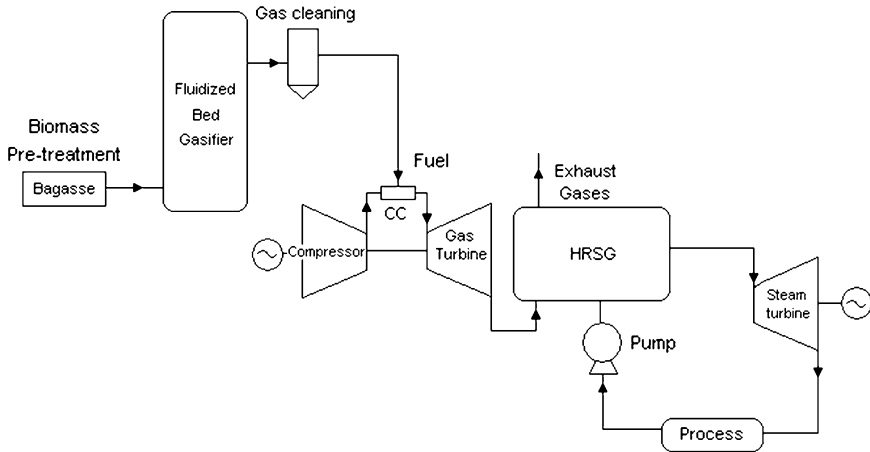


Fig. 18.6 Cogeneration combined cycle associated with the fluidized bed gasifier

a fluidized bed is 800–850 °C. Air is blown through the bed at a sufficient velocity to keep the bed materials in a state of suspension. The fuel particles are introduced at the bottom of the reactor, very quickly mixed with the bed material, and almost instantaneously heated up to the bed temperature and hence the subsequent producer gas generation. After the producer gas has left the fluidized bed chamber, it goes through a cleaning unit. The gas after the cleaner unit is then led to a boost compressor that compresses it to the gas turbine combustion chamber pressure conditions. The exhaust heat from the combustion turbine is recovered in the heat recovery steam generator to produce steam. This steam then passes through a steam turbine to power another generator, which produces more electricity. The combined cycle is more efficient than conventional power generating systems because it reuses waste heat to produce more electricity (Okure et al. 2006).

18.3.5.1 Energy Analysis of the Integration of Gasification of Bagasse in the Sugar and Alcohol Sector

The energy analysis comprises the study based on the first law of thermodynamics, the law of conservation of energy. This type of study is universally valid and is used in the mass and energy balances in the gasifier and other components of the BIG/GTCC system. For realization of this energy, analysis is determined of the operating parameters and efficiencies of the process and its components. However, only the use of the first law of thermodynamics proves to be insufficient in subsequent economic evaluation of an energy system, because it does not estimate the amount of energy available for conversion into work or power. Given this, the study based on only the first law of thermodynamics gives us an incomplete analysis of the potential energy of a system.

18.3.5.2 Exergetic Analysis of Integration of Gasification of Bagasse in the Sugar and Alcohol Sector

Given the limitations of the first law in formulating the quality and quantity of useful energy in a system, the concept of Exergy was created from the second law of thermodynamics. According to Tuna (1999), Exergy is that portion of noble energy that can be completely converted into work reversibly. However, the exergy can be defined as the maximum useful work that can be obtained by an energy carrier (Tsatsaronis 1993). The exergy inefficiency of a system consists in a destruction of exergy associated with irreversibilities. The irreversibility in a system can be decomposed into internal irreversibility, known as the Second Law of Thermodynamics as destruction of energy and external irreversibility, which is the exergy loss to the environment, developing out of the control volume selected for thermodynamic analysis (Valero et al. 2011). The maximum improvement in exergy efficiency for a process or system is obviously determined when the exergy loss or irreversibility is minimized, the latter being determined by the following equation (Sozen et al. 2002; Utlu et al. 2006):

$$I = \sum E_{x_{in}} - \sum E_{x_{out}} \quad (18.12)$$

$$e_{x1} = (h_1 - h_0) - T_0(S_1 - S_0) \quad (18.13)$$

$$E_{x1} = m \cdot e_{x1} \quad (18.14)$$

Exergy analysis or even availability analysis is then drawn in this way to achieve the goal of a more effective use of energy resource as it enables the location, cause, and true magnitude of waste and loss. Such information can be used in the design of efficient energy systems and to increase the performance of existing systems. Exergy analysis also provides a broader view of the problem under consideration, avoiding conclusions based purely on the application of the

first law of thermodynamics. Tuna (1999) emphasizes that the analysis of first and second law are not competing, but complementary, and together contribute to a consistent assessment of the thermal system.

18.4 Economic Analysis

In both technologies the methodology to make the economic analysis is similar and is based on engineering economics calculations developed by Silva (2010), who considered the sugarcane industry producing hydrogen using ethanol and gasification of electricity generated in the gas turbine and steam turbine by use of producer gas from bagasse gasification. In order to reach this proposal, an economic analysis based on the investment of the hydrogen production system and BIG/GTCC system were developed considering the input costs, operating cost, maintenance cost, operation period, interest rate, and annuity factor.

The global equation for hydrogen cost is shown in the following equation:

$$C_{H_2} = \frac{I_{\text{nvref}} \cdot f}{H \cdot E_{H_2}} + C_{\text{OP}} + C_{\text{man}} \quad (18.15)$$

The annual cost of obtaining electricity (C_{el}), US\$/kWh, for each selected system is given as

$$C_{\text{el}} = \frac{(I_{\text{pl}} - I_{\text{vcr}}) \cdot f}{H \cdot E_p} + \frac{C_{\text{comb}} \cdot (E_{\text{comb}} - E_{\text{cr}} - \frac{\text{Per}}{2})}{E_p} + \text{CM}_{\text{stg}} \quad (18.16)$$

$$f = \frac{q^k \cdot (q - 1)}{q^k} \quad (18.17)$$

where:

k is the amortization period or pay-back, given in years. C_{H_2} —Hydrogen production cost (US\$/kWh); C_{el} —Electricity production cost (US\$/kWh); I_{nvref} —Reference investment for hydrogen production ($\times 10^4$ US\$); f —Annuity factor (1/year); H —Equivalent period of operation (h/year); E_{H_2} —Energy provided by Hydrogen (kW); C_{op} —Operational cost (US\$/kWh); C_{man} —Maintenance cost (US\$/kWh).

Operational cost using bagasse as fuel is shown in Eq. 18.18, and the operational cost using electricity is shown in Eq. 18.19. According to Kothari et al. (2008), the maintenance cost of steam reformer was estimated as 3 % of investment.

$$C_{\text{OP}} = \frac{E_{\text{fuel}} \cdot C_{\text{fuel}}}{E_{H_2}} + \frac{E_{\text{EtOH}} \cdot C_{\text{EtOH}}}{E_{H_2}} \quad (18.18)$$

$$C_{\text{OP}} = \frac{E_{\text{Elet}} \cdot C_{\text{Elet}}}{E_{H_2}} + \frac{E_{\text{EtOH}} \cdot C_{\text{EtOH}}}{E_{H_2}} \quad (18.19)$$

where:

- E_{fuel} Energy provided by sugarcane bagasse (kW);
- C_{fuel} Fuel cost (sugarcane bagasse) (US\$/kWh);
- E_{EtOH} Energy provided by ethanol (kW);
- C_{EtOH} Ethanol cost (US\$/kWh);
- E_{Elet} Electricity consumed by reformer (kW);
- C_{Elet} Electricity cost (US\$/kWh).

The investment cost (acquisition cost of equipment, installation cost) to produce steam covers the cost of system gas turbine (compressor, combustion chamber, gas turbine electric generator, and other accessories), the heat recovery steam generator is considered as separate module. Thus, the following equation is used to calculate the investment to be made:

$$I_{\text{pl}} = I_{\text{stg}} + I_{\text{vcr}} \quad (18.20)$$

For investment cost of heat recovery steam generator (I_{vcr}) without supplemental fuel burning is used Eq. 18.21, defined as the technique of Boehn (1987) according to the steam production in (kg/h), with a multiplicative factor of 10 % related to the cost of installation of the boiler recovery and valid for production values higher than 800 kg/h and less than 4000 kg/h.

$$I_{\text{vcr}} = 1.1 * 160000 * \left(\frac{m_v}{1500} \right)^{0.81} \quad (18.21)$$

The equation final investment cost becomes:

$$I_{\text{pl}} = (I_{\text{stg}} + I_{\text{vcr}}) * 1.3 \quad (18.22)$$

$$C = C_r \left(\frac{S}{S_r} \right)^m \quad (18.23)$$

where:

C —Equipment cost for an interest capacity S ; m —Incidence factor indicating the economics scale (0.5–1.0); C_r —Equipment cost for a reference capacity S_r .

Silva (2010) has adapted the reference investment for steam reforming process with hydrogen production range of 1 up to 1500 (Nm^3/h), resulting in Eq. 18.24

$$\text{Inv}_{\text{ref}} = \left(\frac{m_{\text{H}_2}}{750} \right)^{0.5304} \quad (18.24)$$

The expected annual revenue is calculated as the sum of earnings or annual benefits due to the installation of a system (Silveira and Tuna 2003, 2004).

18.5 Ecological Analysis

At present, practically all known forms of energy production have some kind of interference in the environment. Due to this fact using biomass gasification combined with a cogeneration system is a set of recommended alternative energy, from the environmental point of view.

18.5.1 Ecological Efficiency

The ecological efficiency analysis is based on calculations of equivalent carbon dioxide $[(CO_2)_e]$, and pollution indicator (Π_g) for determining the ecological efficiency of the process of hydrogen production by ethanol steam reforming, and for the BIG/GTCC system.

18.5.2 Determination of Equivalent Carbon Dioxide (CO_{2e})

The equivalent carbon dioxide depends on the emission of SO_2 , NO_x , and PM, and can be determined using Eq. 18.25.

$$CO_{2e} = CO_2 + 80 * SO_2 + 50 * NO_x + 67 * MP \quad (18.25)$$

18.5.3 Determination of Pollution Indicator (Π_P)

The pollution indicator (Π_P) is the ratio between the amount of CO_{2e} in kg and the power supplied by the producer gas and for the hydrogen production it is shown in Eq. 18.26 (Silveira et al. 2012).

$$\Pi_P = \frac{CO_{2e}}{PCI} \quad (18.26)$$

18.5.4 Determination of Ecological Efficiency (ε)

Ecological efficiency is defined as an indicator for evaluating the performance of a particular system, considering the emissions of pollutants burning 1 kg of fuel. Their values vary between 0 and 1, where the higher the vicinity of 0 means the greater the environmental impact, and if it is proximate to 1, indicates that it is

nonpolluting (zero environmental impact). The ecological efficiency can be determined using Eq. 18.27 (Silveira et al. 2012).

$$\varepsilon = \left[\frac{0.204 * \eta_{\text{system}} * \ln(135 - \Pi_p)}{\eta_{\text{system}} + \Pi_p} \right]^{0.5} \quad (18.27)$$

18.5.5 Calculation of CO₂ Emissions from Combustion Process of Sugarcane Bagasse

The CO₂ emissions from 1 kg of fuel can be calculated according to Eq. (18.28).

$$M = \frac{(w_1 \times 44 \times 1) \text{CO}_2}{N} \quad (18.28)$$

where:

M_{CO_2} —CO₂ emissions (kg_{CO₂}/kg_{fuel}); Molar mass of fuel (bagasse) (kg/kg_{mol}).

The molar mass of bagasse can be determined based on the elemental composition (Table 18.2). Therefore, the molar mass of bagasse can be calculated through Eq. 18.27.

$$N = (a_1 12) + (b_1 1) + (c_1 16) + (d_1 14) + (e_1 32) \quad (18.29)$$

18.6 Conclusions

Hydrogen, the principal energy carrier to fuel cells, can be produced through various ways, but ethanol steam reforming is an alternative to guarantee the volume of production necessary in the Brazilian case. The integration or association of hydrogen production with sugar industry, can certainly put Brazil in a good classification in the “Hydrogen Era,” in the near future. Similarly in terms of ecological efficiency, the fluidized bed gasifier operating with bagasse is an environmentally friendly way, with high ecological efficiency to produce energy in the sugarcane industry. This technology proves that this type of combine cycle is an excellent alternative to the traditional electric power generation technology, based on the Rankine cycle, used in this industry for electricity and heat generation. Thus, these technologies can be inserted with energy and environmental gains in the sugarcane industry.

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