ROLE OF BIOGAS REFORMING FOR HYDROGEN PRODUCTION IN BRAZIL'S ENERGY TRANSITION

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ABSTRACT

In the context of the Paris Agreement, several countries have set forth ambitious global goals aimed at stabilizing and reducing carbon emissions. One of the primary avenues to accomplish these goals is through the concept of energy transition. Within the scope of this study, energy transition is defined as the progression towards economically sustainable and renewable energy technologies, which play a crucial role in mitigating the impacts of climate change. Researchers have engaged in extensive discourse regarding the viability of biogas as a viable fuel source for hydrogen production. This discourse underscores the considerable potential of biogas in waste energy management and harnessing. This research undertakes a comprehensive literature review that delves into the multifaceted role of biogas in achieving cost-effective and ecologically sound hydrogen production. This investigation pays particular attention to nations undergoing development, such as Brazil, which possess significant, yet untapped, biogas potential, the process of biogas reformulation emerges as a highly promising approach not only for hydrogen gas generation but also for mitigating the demand for natural gas. This strategy holds the potential to significantly contribute to the global goals of the energy transition and the global reduction of carbon emissions.

Keywords: Biogas, Energy transition, Hydrogen, Sustainability, Waste management.

Introduction

The escalating demand for energy and the ecological ramifications tied to high greenhouse gas emissions in the atmosphere have heightened the pursuit of alternative energy generation methods. Energy transition denotes the shift towards technologies that reduce greenhouse gas emissions, such as the utilization of renewable energies. These energies are both environmentally and economically sustainable, boasting superior energy efficiency, thereby aiding in the mitigation of climate change. While Brazil's electricity matrix is highly renewable (82.9%), but the energy matrix continues to hinge on fossil fuels (48.4%), particularly within the transportation sector [1]. Consequently, the nation must embark on a comprehensive energy transition encompassing both production and consumption. Emission reduction initiatives must extend beyond the scope of electric energy.

Hydrogen (H_2), a clean fuel, holds the potential to decarbonize the global energy supply. However, similar electric energy, the production of hydrogen necessitates a primary energy source. Presently, over 95% of globally produced hydrogen is obtained from fossil fuels via processes like natural gas reforming and coal gasification [2]. While natural gas contributes to energy transition by mitigating emissions compared to coal, a more sustainable alternative involves producing hydrogen from biogas. Biogas predominantly comprises CH_4 (50% to 75%), a key constituent of natural gas. Hence, the technology of natural gas reforming can be adapted to generate hydrogen from biogas. Furthermore, biogas can be sourced from geographically diverse renewable sources such as agricultural waste, organic waste, sewage, and other organic materials [3].

Renewable sources are directly or indirectly derived from plants that absorb CO_2 from the atmosphere during growth, rendering biogas more sustainable than natural gas. In essence, the conventional use of natural gas for hydrogen production can be substituted with biogas—a renewable resource. This concept has been in circulation since the 1990s [4].

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In the Brazilian context, transitioning to a hydrogen-based economy will only be pragmatic if grounded on low-carbon H_2. However, this endeavor is intricate, as industries reliant on fossil fuels must undergo substantial reorganization to endorse the shift towards a greener economy. Every feasible avenue for facilitating the transition to H_2 must consider factors such as the influence of climate change on productive sectors, the availability of essential commodities for green energy production, technological devices, as well as the nation's capacity to innovate, formulate, and integrate value chains centered around green H_2 [5].

In Europe, the Hydrogen Strategy—a legislative framework striving to integrate hydrogen into Europe's energy transition—articulates both the enduring objective of incorporating renewable hydrogen and the short-term backing for low-carbon hydrogen production methods [6]. This is imperative because the viability of renewable hydrogen hinges on comprehensive research into methods and technology, aimed at constructing a sustainable and workable economic model. Notably, costs associated with hydrogen production from fossil fuels are significantly lower, priced at $1.25 per kg of hydrogen in contrast to the projected cost of $2 per kg of hydrogen for green hydrogen by 2030 [7]. While electrolyzing water via renewable sources (wind and solar) generally represents the costliest technological pathway for hydrogen production available in the market, hydrogen sourced from carbon-containing feedstocks must outperform electrolytic green hydrogen in terms of sustainability. However, hydrogen derived from biogas might prove more appealing both environmentally and economically than electrolytic green hydrogen, particularly when exploiting agricultural and industrial residues [8]. Moreover, the technological maturity and available infrastructure, coupled with carbon capture and storage practices, adoption of energy-efficient routes, and the evolution of novel materials and catalytic reactors, justify the renewed interest in reforming technologies. Consequently, biogas could play a pivotal role in the decarbonization of the economy over the next five decades [5, 9]. Thus, in comparison to the use of natural gas (a fossil fuel), approaches involving biogas for hydrogen production appear more enticing and promising for Brazil's energy transition in the short and medium term. This study reviews the literature on the role of biogas in the production of cheap and environmentally friendly hydrogen, especially in developing countries like Brazil, which has a large biogas production potential that is being wasted.

Biogas Production Potential in Brazil

Biogas production in Brazil reached 2.3 billion Nm^3 in 2021, equivalent to approximately 3% of the country's theoretical potential of 84.6 billion Nm^3 [10]. This highlights notable energy wastage. The biogas landscape in Brazil for 2021 [10] indicates a remarkable 20% growth compared to the reported biogas facilities in 2020 (675 facilities). In 2021, the country witnessed 755 operational biogas plants, with an additional 44 in the implementation phase and 12 undergoing reformulation or refurbishment, resulting in a cumulative count of 811 biogas plants. This trend underscores the consistent expansion within the biogas market.

Brazil occupies a significant position as a global meat producer, notably in poultry, beef, and pork. Estimating a yield of 0.18 kg/day of biogas per poultry unit, researchers have projected that broiler chickens could potentially generate around 55 million Nm^3/year of biogas, whereas laying hens could yield approximately 9.9 million Nm^3/year of biogas [11]. The country also boasts substantial potential for biogas production from plant sources. Notably, the sugarcane sector in the 2019-2020 harvest seasons could yield a remarkable 40 billion Nm^3/year of biogas. Furthermore, cassava, corn, and soy represent potential sources for biogas production, with estimated capacities of 0.66, 6.57, and 5.02 billion Nm^3/year, respectively [11]. Beyond these, numerous other biomass sources exhibit significant promise for biogas generation. Table 1 provides an overview of the annual potentials for biogas, biomethane, and equivalent electricity generation across the sugarcane, agro-industrial, and sanitation sectors.

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Table 1 – Biogas Potential in Brazil – adapted from BNDES (apud [11]).

Origin	Biogas volume (billion m³/year)	Biomethane volume (billion m³/year)	Equivalent electricity generation (GW/year)
Sugarcane	39.76	21.06	85.17
Agro-industrial	38.39	19.55	72.10
Sanitation sectors	6.84	2.62	10.28

Processes for Reforming Methane into Hydrogen

Production of hydrogen from biogas necessitates a reforming reaction that transforms methane into hydrogen. Based on the chosen species for the CH_4 to H_2 oxidation, reforming reactions can be classified into dry reforming, steam reforming, partial oxidation of methane, and autothermal reforming.

A. Dry reforming process

The process of dry reforming entails the utilization of partially treated biogas (free from H_2S) in thermochemical processes, conducted at temperatures ranging between 700 and 800°C, under atmospheric pressure, employing catalysts within a fixed-bed reactor. In the dry reforming procedure, the resultant product is synthesis gas (2 CO + 2 H_2) demonstrated in equation 1, subsequently enabling the conversion of this carbon monoxide (CO) into carbon dioxide (CO_2) and hydrogen, thereby amplifying the efficiency of the system, as shown in equation 2. However, it is important to note that this process involves two greenhouse gases, features decentralized H_2 production, and exhibits an increased propensity for the formation of "coke" [12].

$$CH_4 + CO_2 \leftrightarrow 2\,CO + 2\,H_2 \qquad (1)$$

$$\text{Eq 1 } \Delta H_{298K} = 247\ kJ/mol$$

Water gas shift reaction: $$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad (2)$$

$$\text{Eq 2 } \Delta H_{298K} = -41{,}2\ kJ/mol$$

B. Steam reform process

The steam reforming process entails the utilization of biogas (methane) and water vapor to yield carbon dioxide and hydrogen gas, demonstrated by equation 3. Nonetheless, the occurrence of this process necessitates a substantial quantity of biogas and exceedingly low concentrations of H_2S—below 10 ppm. To facilitate the reaction, favorable conditions encompassing temperature, water vapor, and catalysts are imperative. Analogous to dry reforming, carbon monoxide can react with water, thereby augmenting the hydrogen production, according to equation 4 [12].

$$CH_4 + 2\,H_2O \leftrightarrow CO + 3\,H_2 \qquad (3)$$

$$\text{Eq 3 } \Delta H_{298K} = 206{,}2\ kJ/mol$$

Water gas shift reaction: $$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad (4)$$

$$\text{Eq 4 } \Delta H_{298K} = -41{,}2\ kJ/mol$$

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C. Partial oxidation of methane process

The process of partial methane oxidation, also known as oxidative reforming, entails heating methane in the presence of a controlled amount of pure oxygen within a reformer. This exothermic reaction is noted for its swifter kinetics compared to steam reforming [13]. Partial oxidation has garnered renewed attention within research circles and industries alike, primarily due to its heightened energy efficiency in contrast to steam reforming. This process yields a hydrogen and carbon monoxide mixture in a 2:1 molar ratio, offering an enticing prospect, coupled with the potential utilization of the resultant carbon monoxide byproduct. The partial oxidation reaction of methane is presented in equation 5.

$$CH_4 + 1/2\ O_2 \leftrightarrow CO + 2\ H_2 \qquad (5)$$
$$\text{Eq 5}\ \Delta H_{298K} = -35{,}6\ kJ/mol$$

D. Autothermal reform process

Autothermal reforming entails the amalgamation of both steam reforming and partial oxidation processes. Typically, two distinct reaction approaches are applied. In the first, a catalytic bed is employed, facilitating the concurrent occurrence of combustion and steam reforming reactions. Meanwhile, the second approach involves the utilization of two segregated sections. The initial section encompasses partial oxidation (equation 6) through the utilization of a burner, followed by the subsequent section where catalytic bed reforms transpire, effecting the conversion of biogas into hydrogen, according to equations 7 to 9.

Combustion zone:

$$CH_4 + 3/2\ O_2 \leftrightarrow CO + 2\ H_2O \qquad (6)$$
$$\text{Eq 6}\ \Delta H_{298K} = -124\ kJ/mol$$

Catalytic and thermal zone:

$$CH_4 + H_2O \leftrightarrow CO + 3\ H_2 \qquad (7)$$
$$\text{Eq 7}\ \Delta H_{298K} = 206{,}2\ kJ/mol$$

Water gas shift reaction:

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad (8)$$
$$\text{Eq 8}\ \Delta H_{298K} = -41{,}2\ kJ/mol$$

$$CH_4 + 2\ H_2O \leftrightarrow CO_2 + 4\ H_2 \qquad (9)$$
$$\text{Eq 9}\ \Delta H_{298K} = 165\ kJ/mol$$

The choice of reforming reaction type and the conditions governing these reactions constitute pivotal considerations within the biogas reforming process, as they exert influence over hydrogen production, susceptibility to carbon formation, and energy efficiency [14]. Generally, reforming reactions are characterized by their endothermic nature, rendering them more favorable under elevated temperature conditions, albeit at the cost of diminished energy efficiency and reduced catalyst longevity [15]. Recent studies have underscored an array of technical and scientific challenges, inclusive of the development of resources that are energy-efficient and catalytic agents that exhibit both heightened activity and resilience against deactivation [16]. The employment of catalysts boasting augmented catalytic activity and stability during the reforming process may pave the way for decreased reliance on conventional high-temperature regimes. This shift holds the potential for improved reaction kinetics and a deceleration in the catalyst deactivation progression.

According to some authors, the cost of hydrogen production from biogas varies from 1.39 to 7.21 USD/kg H_2, depending on the type of reforming reaction, process configuration and capacity [17-19].

Braga et al. conducted an economic and ecological analysis of H_2 production by steam reforming of biogas and reported the process was economically feasible and free from causing environmental impacts due to the high value of ecological efficiency, 94.95%, even without considering the cycle of CO_2. The cost for H_2 production was estimated to be 0.27 US$/kWh with a payback period of eight years [20].

Presently, investigations pertaining to biogas reforming for hydrogen production within the Brazilian context remain relatively scarce.

Advantages of Hydrogen Generation from Biogas

Harnessing the potential of biogas offers a promising strategy for curbing greenhouse gas emissions, contrasting favorably with the utilization of fossil fuels. Derived from renewable biomass and animal waste, biogas production boasts economic advantages owing to its low-cost resource base, coupled with its ready availability in ample quantities. This becomes particularly pertinent in the context of hydrogen (H_2) production, where biogas presents a cost-effective and environmentally conscientious avenue, particularly salient in developing economies such as Brazil. The process of biogas reforming emerges as not only a method to facilitate H_2 production but also a means to alleviate the demand for natural gas resources. In the current landscape, hydrogen production has assumed a paramount role within the renewable energy discourse, propelled by the pressing global energy demand, depletion of fossil fuel reserves, ecological imperatives, and the advancing frontier of fuel cell technology. The utilization of biogas serves as a catalyst for waste management and sustainable progress in both rural and urban environments [16].

Critical to note is that the challenges encountered thus far, coupled with those on the horizon, pale in comparison to the advantages offered by biogas reforming. This is underpinned by the fact that the hydrogen synthesized through this channel is inherently renewable, aligning seamlessly with principles of sustainability. The adoption of biogas reforming for hydrogen production not only facilitates the recycling of biogas resources but also represents a transformative process wherein polluting gases (CH_4 and CO_2) find purpose as inputs for industrial processes [21].

Moreover, scholars underscore the pivotal role of biogas in advancing Sustainable Development Goals (SDGs). Notably, this encompasses SDG-6's pursuit of Clean Water and Sanitation, SDG-7's vision of Affordable and Clean Energy, SDG-9's focus on Industry, Innovation, and Infrastructure, SDG 11's commitment to Sustainable Cities and Communities, SDG-12's advocacy for Responsible Consumption and Production, and finally, SDG-13's mandate for Climate Action [21]. Equally deserving of attention is the sustainability of the biogas and H_2 supply chain, as well as the untapped potential of waste as a wellspring of sustainable energy, offering a promising avenue for diminishing reliance on fossil fuels [22].

Conclusion

Hydrogen, more than a mere fuel, serves as a carrier of chemical energy, enabling its conversion into electricity and essential compounds for both the chemical and petrochemical industries, as well as the transportation sector. The burgeoning interest in harnessing renewable sources of hydrogen is projected to continue its upward trajectory in the coming years, further amplifying the demand for this versatile element. This underscores the critical role of sustainable hydrogen production, which hinges not only on the process's carbon footprint but also on the judicious allocation of energy resources.

Despite the identification of technical, economic, and environmental limitations, hydrogen (H_2) perseveres as a compelling candidate for effecting decarbonization, or at the very least, for curbing greenhouse gas emissions within pivotal sectors like transportation, petrochemicals, and steel manufacturing.

In the context of Brazil, biogas reformulation emerges as a captivating pathway toward realizing "green" hydrogen production. This proposition gains significance within the context of an imperative energy transition that demands the integration of renewable feedstocks across a wider spectrum of activities. This transition entails the cultivation of ecologically responsible production processes and the sustainable stewardship of invaluable natural resources.

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