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4E Analysis and Multi-Objective Optimization of Hydrogen Production via Biomass Gasification

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Extended Abstract

Introduction

The growing global energy crisis, environmental concerns caused by greenhouse gas emissions, and the urgent need to reduce dependence on fossil fuels have driven the development of renewable and clean energy technologies. Among these, hydrogen has emerged as a promising energy carrier due to its high energy density and carbon-free combustion product—water. However, the sustainable and cost-effective production of hydrogen remains one of the major challenges to realizing the “hydrogen economy.”

One of the most promising pathways for renewable hydrogen production is biomass gasification, a thermochemical process that converts biomass into a combustible gas mixture known as syngas. Biomass, being a carbon-neutral, abundant, and renewable resource, offers significant potential for clean fuel generation. Among various biomass types, sugarcane bagasse is particularly attractive due to its high availability, low cost, and non-competition with the food supply chain. In this study, a comprehensive 4E analysis (Energy, Exergy, Economic, and Environmental) was conducted on a hydrogen production system based on sugarcane bagasse gasification. The system is further optimized using a multi-objective optimization approach employing the Artificial Bee Colony (ABC) algorithm to maximize energy and exergy efficiencies while minimizing total cost and CO_2 emissions.

Materials and Methods

The proposed system consists of four main subsystems: a dryer, a gasifier, a water–gas shift (WGS) reactor, and a hydrogen separation unit. The overall process converts raw biomass into hydrogen-rich syngas through a sequence of thermochemical and catalytic reactions. Air is used as the oxidizing agent in the gasifier to initiate partial combustion reactions and generate the heat required for subsequent endothermic processes. The sugarcane bagasse feedstock first passes through a drying unit, where its moisture content is reduced using recovered thermal energy. In the gasifier, the dry biomass undergoes pyrolysis in the absence of oxygen, decomposing into volatile gases, char, and tar. These products react with air and steam to produce syngas, a mixture primarily composed of H_2, CO, CO_2, and CH_4. The hot syngas exiting the gasifier transfers its heat through a heat exchanger, where the recovered heat can be utilized for power generation or process heating, enhancing the system’s overall efficiency. The resulting hydrogen-enriched gas stream is subsequently fed into a separation unit, where hydrogen is purified from other gases such as CO_2 and N_2. This separation is typically achieved through pressure swing adsorption (PSA) or membrane-based techniques. The system performance was analyzed using energy, exergy, economic, and environmental criteria. The Artificial Bee Colony (ABC) algorithm was employed to optimize the operating parameters—including gasification temperature, biomass moisture content, and syngas pressure—with the objective of improving.

Results and Discussion

Initial results of the base case showed that the system achieved energy and exergy efficiencies of 21.34% and 21.12%, respectively. After the optimization process, these efficiencies increased to 23.12% and 21.43%, indicating a clear

enhancement in thermodynamic performance. Simultaneously, both the total cost and CO_2 emission rate decreased, demonstrating the effectiveness of the multi-objective optimization approach.
The exergy analysis revealed that the gasifier is the largest source of irreversibility within the system, making it the most significant contributor to exergy destruction and operating cost. From the environmental perspective, the gasification-based process exhibited substantially lower carbon emissions compared with conventional fossil-fuel-based hydrogen production methods. Moreover, the potential for achieving a negative carbon footprint was observed under specific operating conditions. A sensitivity analysis was also conducted to examine the impact of key parameters. It was found that increasing the gasification temperature and decreasing the biomass moisture content significantly improved both energy and exergy efficiencies without causing negative economic or environmental consequences. Conversely, increasing the syngas pressure led to higher system costs and emissions with only marginal efficiency improvements, making it an undesirable condition.

Conclusion

This research presented a comprehensive study on clean hydrogen production from sugarcane bagasse gasification using a 4E analysis framework (energy, exergy, economic, and environmental) combined with multi-objective optimization via the Artificial Bee Colony algorithm. The findings confirmed that:

• The gasifier is both the most exergy-destructive and cost-intensive component of the system.

• The proposed system exhibits a lower carbon footprint compared to fossil-fuel-based hydrogen production.

• The optimization successfully improved the system's thermodynamic performance and economic feasibility.

• Increasing gasification temperature and reducing biomass moisture are the most effective parameters for efficiency enhancement.

In conclusion, the proposed system provides a highly efficient, environmentally friendly, and economically viable approach for hydrogen generation from biomass. The developed analysis and optimization framework can serve as a powerful tool for the design and development of future sustainable hydrogen production technologies.

Keywords: hydrogen production, biomass gasification, sugarcane bagasse, 4E anaylsis, Multiobjective optimization

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