Innovative Energy System Using Sonic Hydrogen and Nuclear Power Generation for a Sustainable Community

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Abstract. This study proposes an innovative approach for hydrogen generation by incorporating sonohydrogen technology into a nuclear-based multigeneration energy system. The proposed system combines nuclear and biomass energy sources to produce electricity, hydrogen, hot water, and fresh water. A small modular reactor serves as the primary power source, supporting sustainable hydrogen production and electricity generation. The system employs biomass-derived biogas for electricity and hydrogen generation, achieving overall energy and exergy efficiencies of 89% and 75%, respectively. This system is capable of producing 80 kg/s of fresh water with an efficiency of 83% in the desalination unit. Through energy and exergy analyses, the study demonstrates the feasibility and efficiency of this advanced multigeneration system in supporting sustainable communities, minimizing environmental impact, and advancing clean energy transitions.

1. Introduction

The global energy landscape is at a critical crossroads. As populations expand and economies grow, the demand for energy has surged to unprecedented levels, fueling the need for innovative solutions to meet this demand sustainably. For decades, fossil fuels such as coal, oil, and natural gas have been the primary energy sources powering industries, homes, and transportation systems. However, their environmental impact, from greenhouse gas emissions to pollution, has raised concerns about their long-term viability.

The increasing focus on sustainable energy solutions has highlighted the need to transition away from fossil fuels toward cleaner alternatives. Among these alternatives, nuclear energy stands out as a reliable and low-carbon source of electricity. Its ability to generate substantial power with minimal environmental impact makes it a compelling option for addressing global energy needs.

Hydrogen production represents one of the most critical areas of innovation in the ongoing clean energy transition. As the world seeks to reduce its reliance on fossil fuels and curb carbon emissions, hydrogen is gaining significant attention for its potential as a versatile and clean energy carrier. Hydrogen production is a crucial process for meeting energy demands and advancing clean energy technologies. It involves utilizing different methods to extract or generate hydrogen efficiently. These methods include sonic, photonic, biological, chemical, thermal, thermochemical, and electrochemical approaches. Among the most exciting advancements in this field is the development of new methods such as sonohydrogen production [1]. This state-of-the-art technology utilizes ultrasonic waves to generate hydrogen in an environmentally friendly manner [2]. This innovation not only paves the way for greener industrial processes but also offers cleaner and more sustainable alternatives for fueling transportation, powering industry, and generating electricity.

Beyond energy production, the agricultural sector also demands sustainable energy inputs, particularly for producing fertilizers essential to feeding the world's growing population [3]. Currently, fertilizer production relies heavily on energy-intensive processes, many of which are powered by fossil fuels. However, renewable energy sources and biomass offer promising alternatives. By harnessing organic materials for energy and raw materials, biomass can reduce dependence on non-renewable resources and contribute to a circular economy.

The transition to sustainable energy is not limited to technological advancements; it requires systemic changes across industries and societies. The integration of alternative energy sources, the adoption of energy-efficient technologies, and the shift toward renewable resources are all critical components of this transformation. Furthermore, governments, businesses, and individuals must collaborate to address the challenges posed by climate change, resource depletion, and energy insecurity. This holistic approach underscores the need to explore diverse energy generation strategies that align with the principles of sustainability and efficiency. The concept of single-generation, cogeneration, trigeneration, and multigeneration systems provides a robust framework for optimizing energy systems in the context of sustainable development. While single-generation systems focus on producing a single energy output, such as electricity, cogeneration and trigeneration systems expand the scope by integrating additional functionalities like heat and cooling. Multigeneration systems take this approach even further, combining multiple energy outputs, including heat, power, hydrogen and cooling, into a unified operation. These advanced systems not only enhance energy efficiency but also reduce overall environmental impact by maximizing resource utilization and minimizing waste. The innovative integration of technologies like sonohydrogen within frameworks offers an exciting opportunity to meet the diverse energy demands of modern communities while paving the way toward a cleaner, more sustainable future.

The main objectives of this research are to explore the innovative integration of sonohydrogen technology within advanced energy systems, evaluate its potential for efficient and sustainable hydrogen production, and assess its role in multigeneration frameworks. This study focuses on conducting comprehensive energy and exergy analyses to quantify the performance, and sustainability of the proposed systems. By leveraging the interactions between nuclear energy, biomass, and emerging technologies, the research aims to develop a scalable model that addresses the growing global demand for clean energy while minimizing environmental impacts. Furthermore, the study seeks to demonstrate how multigeneration systems can optimize resource utilization, reduce waste, and support sustainable communities through a unified and holistic energy approach.

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2. System Description

The proposed integrated energy system combines nuclear and biomass energy sources to produce electricity, and hydrogen, while utilizing waste heat for fresh water and hot water. This multigeneration system is designed to optimize resource utilization, minimize waste, and support sustainable communities through innovative technologies.

As shown in Figure 1, the biomass subsystem begins with the collection of organic waste, which is processed in an anaerobic digester. This process produces biogas, consisting mainly of methane and carbon dioxide. The biogas stream is then divided into two primary uses. Half of the biogas is directed to a Brayton cycle, where it serves as fuel for a gas turbine. The other half of the biogas is used in a steam methane reforming unit to produce hydrogen. In this process, methane reacts with steam to yield hydrogen and carbon dioxide. The hydrogen is stored and distributed for various applications, including fueling hydrogen-powered vehicles and supporting industrial processes.

The nuclear subsystem employs a small modular reactor to generate the majority of the system's electricity. This electricity is primarily allocated for sonohydrogen production, an innovative method that utilizes ultrasonic waves to produce hydrogen from water.

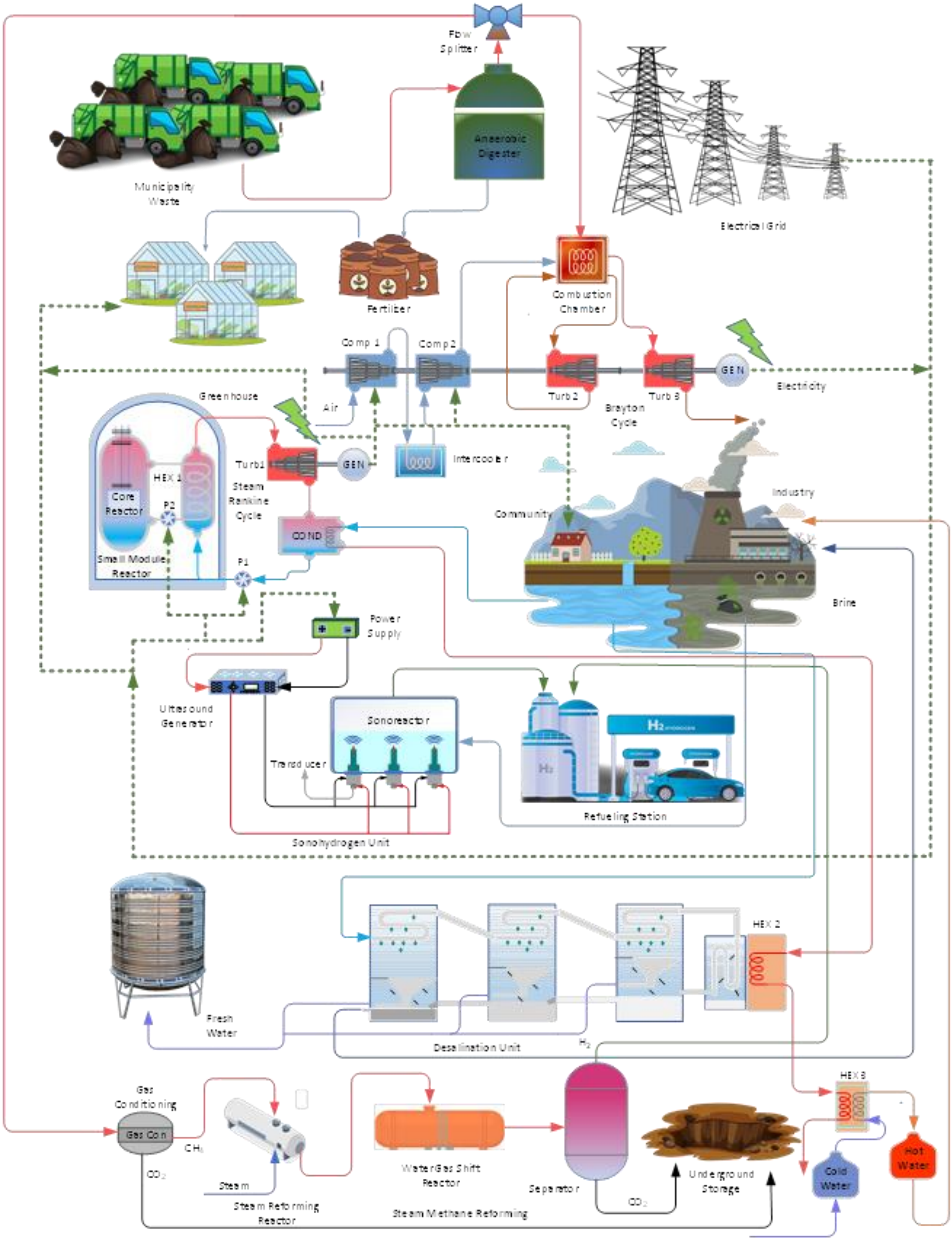

Figure 1: A schematic diagram of the integrated energy system

By powering ultrasonic devices with electricity from the nuclear reactor, the system achieves enhanced reaction rates and minimized energy losses compared to conventional electrolysis, ensuring efficient, sustainable, and green hydrogen generation. Additionally, any surplus electricity from the nuclear subsystem can be supplied to the power grid to meet additional community demands or stored for later use.

The system is also equipped to provide fresh water by capturing and utilizing waste heat from nuclear reactor. This thermal energy is transferred through a network of heat exchangers to supply hot water for residential and industrial heating needs. A cold water return system ensures efficient energy circulation within the district heating loop, further enhancing the system's overall efficiency.

The integration of these subsystems into a single energy framework ensures maximum resource efficiency. By splitting biogas between electricity and heat production and hydrogen generation, the system effectively balances the dual demands of power and clean fuel production. Waste heat is repurposed for hot water and fresh water, reducing overall energy wastage. Furthermore, the hydrogen produced from steam methane reforming, and sonohydrogen technologies support clean energy transitions in transportation, industrial applications, and energy storage. This innovative multigeneration system is designed to reduce greenhouse gas emissions by replacing fossil fuels with renewable and nuclear energy sources. It supports circular economy principles by utilizing organic waste for energy production and enhances energy security and sustainability by integrating diverse energy outputs, including electricity, heat, and hydrogen, into a unified operation.

3. Thermodynamics analysis

This section provides an evaluation of the system's thermodynamic performance. The energy and exergy balance equations for the main components of the system are presented in Table 1.

Table 1: Equations representing the balance for the system components **[4]**

Component	Energy balance equations / Exergy balance equations
Compressor	$\dot{m}_{in}h_{in} + \dot{W}_{COMP} = \dot{m}_{out}h_{out}$ $\dot{m}_{in}ex_{in} + \dot{W}_{COMP} = \dot{m}_{out}ex_{out} + \dot{E}xd_{COMP}$
Condenser	$\dot{m}_{in}h_{in} = \dot{m}_{out}h_{out} + \dot{Q}_{COND}$; if Tin> Tout $\dot{m}_{in}h_{in} + \dot{Q}_{COND} = \dot{m}_{out}h_{out}$; if Tin< Tout $\sum \dot{m}_{in}ex_{in} = \sum \dot{m}_{out}ex_{out} + \dot{E}xd_{COND}$
Pump	$\dot{m}_{in}h_{in} + \dot{W}_{Pump} = \dot{m}_{out}h_{out}$ $\dot{m}_{in}ex_{in} + \dot{W}_{pump} = \dot{m}_{out}ex_{out} + \dot{E}xd_{Pump}$
Heat exchanger	$\dot{m}_{in}h_{in} = \dot{m}_{out}h_{out} + \dot{Q}_{HEX}$; if Tin> Tout $\dot{m}_{in}h_{in} + \dot{Q}_{HEX} = \dot{m}_{out}h_{out}$; if Tin< Tout $\sum \dot{m}_{in}ex_{in} = \sum \dot{m}_{out}ex_{out} + \dot{E}xd_{HEX}$
Turbine	$\mathbf{\dot{m}_{in}h_{in} = \dot{m}_{out}h_{out} + \dot{W}_{Turbine}}$ $\dot{m}_{in}ex_{in} = \dot{m}_{out}ex_{out} + \dot{W}_{Turbine} + \dot{E}xd_{Turbine}$

The overall energy and exergy efficiencies are defined below:

$$\eta_{System} = \frac{\dot{m}_{H_2}LHV_{H_2} + \dot{W}_{net} + \dot{Q}_{heat} + \dot{Q}_{hot\,water}}{\dot{m}_{biomass}LHV_{biomass} + \dot{Q}_{Nuclear}} \quad (1)$$

$$\psi_{System} = \frac{\dot{m}_{H_2}e_{ch,H2} + \dot{W}_{net} + \dot{E}x_{heat} + \dot{E}x_{hot\,water}}{\dot{m}_{biomass}e_{ch,biomass} + \dot{E}x_{Nuclear}} \quad (2)$$

where η_{System} and ψ_{System} are overall energy and exergy efficiencies of the system. In addition , $\dot{m}_{H_2} LHV_{H_2}$ represent chemical energy of hydrogen products from both steam methane reforming and sonic method, $\dot{W}_{net}$ is net power, $\dot{Q}_{heat}$ shows useful heat output for fresh water, $\dot{Q}_{hot\,water}$ shows useful hot water, and $\dot{m}_{biomass} LHV_{biomass}$ represents energy from biomass and $\dot{Q}_{Nuclear}$ is nuclear energy. Moreover, $\dot{m}_{H_2} e_{ch,H2}$ shows chemical exergy of hydrogen products, $\dot{m}_{biomass} e_{ch,biomass}$ shows chemical exergy of biomass and $\dot{Ex}_{Nuclear}$ represent exergy of nuclear heat input.

4. Results and discussion

Figure 2 shows the overall performance of the integrated energy system in terms of energy and exergy efficiencies. The system demonstrates a high overall energy efficiency, reaching 89 %, highlighting its ability to effectively convert input energy sources into useful outputs. Additionally, the exergy efficiency is slightly lower, at 75 %, reflecting the system's effectiveness in preserving the quality of energy during the conversion processes.

Figure 3 illustrates the impact of varying the biogas mass flow rate on both energy and exergy efficiencies of the proposed system. The energy efficiency increases steadily with the biogas flow rate, starting from 76.2 % at a mass flow rate of 6000 kg/h and reaching 82.7 % at 7200 kg/h. Similarly, the exergy efficiency follows a consistent upward trend, beginning at about 59.8 percent for a biogas mass flow rate of 6000 kg/h and rising to 68.3 % at 7200 kg/h. This trend demonstrates the system's ability to convert higher biogas input into improved energy and exergy performance. The gradual increase in efficiency highlights the system’s capability to optimize resource utilization and enhances the overall performance, particularly as the biogas input increases. These results underline the potential of the integrated system in achieving high operational efficiency, making it a promising solution for sustainable energy production.

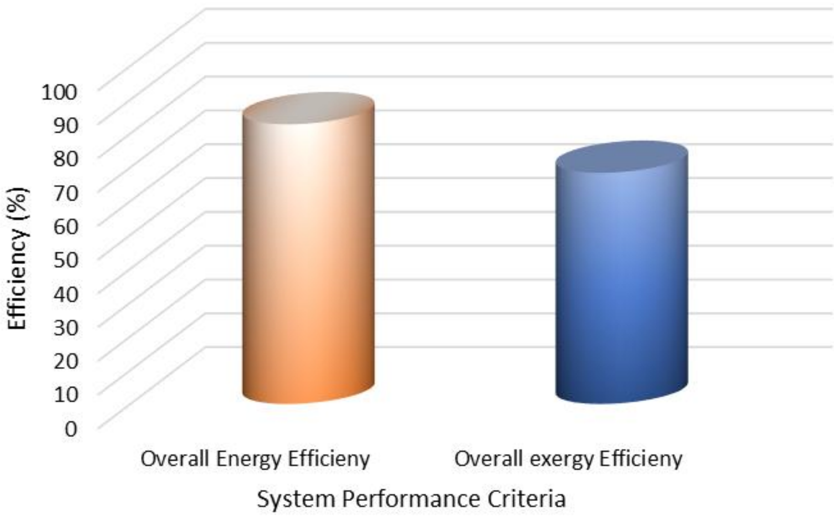

Figure 2: Overall performance of the integrated system

The results illustrated in Figure 4 show the relationship between the biogas mass flow rate and the corresponding outputs of electricity and total hydrogen production. This electricity represents the energy directly available for community use, having already accounted for the energy consumed in hydrogen production. As the biogas mass flow rate increases from 6000 kg/h to 7200 kg/h, there is an increase in both electricity output and total hydrogen production. Electricity output rises from 720.27 kW at a biogas flow rate of 6000 kg/h to 3253.20 kW at 7200 kg/h, signifying the ability of the system to deliver more power to the community as more biogas is supplied. Similarly, total hydrogen production increases from 938.64 kg/h to 1119.58 kg/h over the same range of biogas mass flow rates.

This trend underscores the scalability of the system, where an increase in biogas availability enhances both electricity generation and hydrogen production. Such a relationship highlights the potential for optimizing biogas input to balance community energy needs and hydrogen output for storage or industrial purposes.

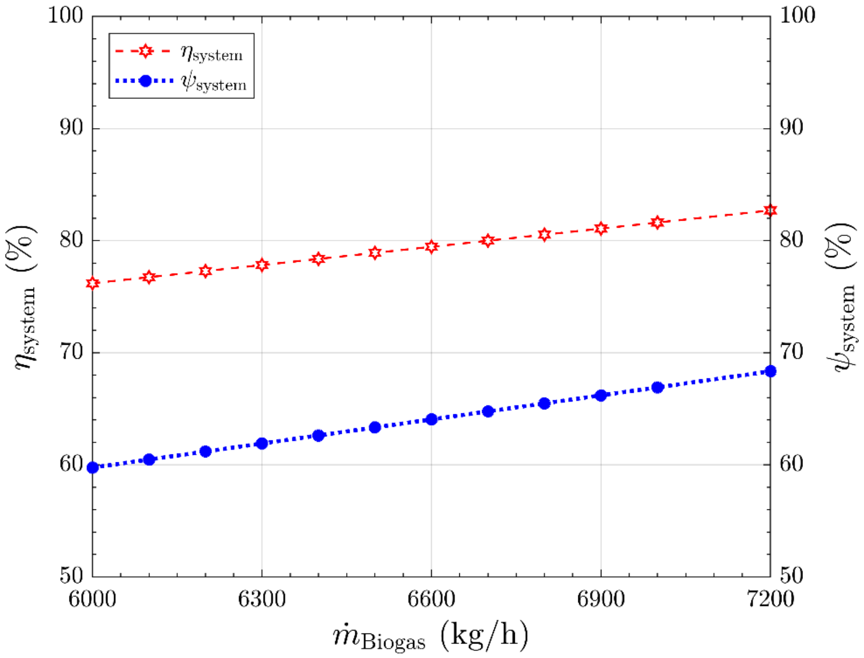

Figure 3. Effect of variation of the biogas mass flow rate on energy and exergy efficiencies

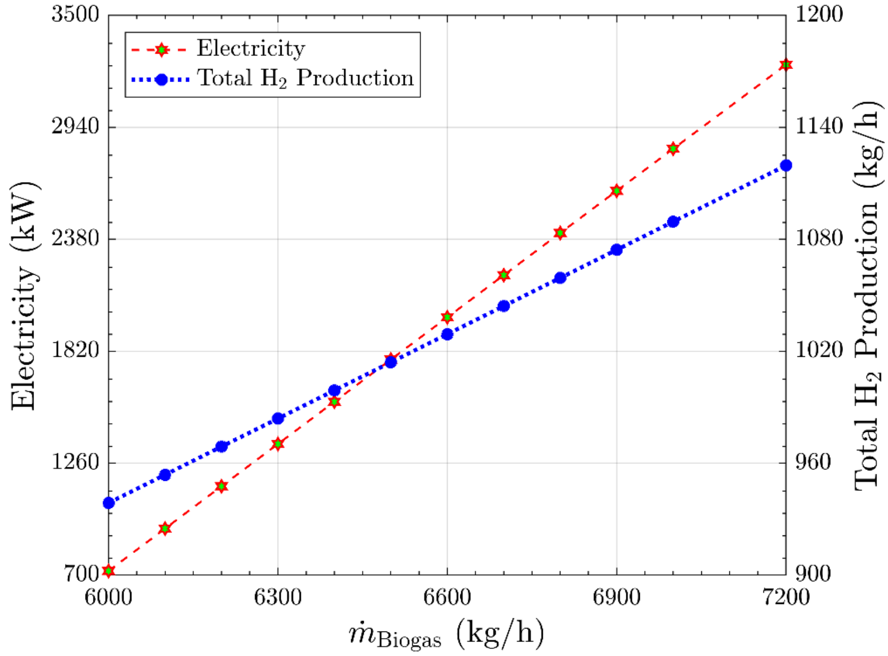

Figure 4. Effect of variation of the biogas mass flow rate on electricity and hydrogen production rate

5. Conclusions

This study demonstrates the potential of integrating sonohydrogen technology into a nuclear-based multigeneration energy system for sustainable hydrogen production. The developed novel system achieves high energy efficiency of 89% and exergy efficiency of 75% by combining nuclear and biomass energy sources to optimize resource utilization and minimize waste. The system can generate 80 kg/s of fresh water with an 83% efficiency rate in the desalination unit. Key findings highlight the advantages of employing ultrasonic waves for hydrogen production, which enhances reaction efficiency and reduces energy consumption compared to conventional methods. The multigeneration system enables the simultaneous production of electricity, hot water, fresh water, and hydrogen while reducing greenhouse gas emissions. This scalable approach underscores the system's potential to adapt to varying biogas input, ensuring operational efficiency and energy sustainability. The integration of nuclear and biomass energy, coupled with advanced hydrogen production methods, aligns with global efforts to transition toward clean and sustainable energy solutions, supporting sustainable communities and addressing future energy challenges effectively.

Nomenclature

$\dot{E}x$	Exergy Rate (kW)
$E\dot{x}d$	Exergy Destruction Rate (kW)
h	Specific Enthalpy (kJ/kg)
$\dot{m}$	Flow Rate of Mass (kg/s)
P	Pressure (kPa)
$\dot{Q}$	Rate of Heat Transfer (kW)
s	Specific Entropy (kJ/kgK)
T	Temperature (℃)
Greek Letters	
η	Energy Efficiency (%)
ψ	Exergy Efficiency (%)
Subscripts	
ch	Chemical
COMP	Compressor
COND	Condenser
HEX	Heat Exchanger
in	Inlet
out	Outlet
Acronyms	
ch	Chemical
COND	Condenser
HEX	Heat Exchanger
in	Inlet
LHV	Lower Heating Value
out	Outlet

References

[1] S S Rashwan, I Dincer and A Mohany 2020 An investigation of ultrasonic based hydrogen production, *Energy*, vol. 205, p. 118006, doi: 10.1016/j.energy.2020.118006.

[2] M Sharifishourabi, I Dincer and A. Mohany 2024 Experimental testing of a novel sonic method for clean hydrogen generation, *International Journal of Hydrogen Energy*, vol. 82, pp. 206–217, doi: 10.1016/j.ijhydene.2024.07.378.

[3] R F Alshebli and Y Bicer 2022 Energy and exergy analysis of a renewable energy-driven ion recovery system for hydroponic greenhouses, *Sustainable Energy Technologies and Assessments*, vol. 53, p. 102628, doi: 10.1016/j.seta.2022.102628.

[4] I Dincer 2020 *Thermodynamics: A Smart Approach*, John Wiley & Son.