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हरित हाइड्रोजन उत्पादन के लिए भा.प.अ. केंद्र में निम्न तापमान वाली जल विद्युत अपघटक प्रौद्योगिकियों का विकास

Development of Low Temperature Water Electrolyser Technologies at BARC for Green Hydrogen Production

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सारांश

आयातित कच्चे तेल पर निर्भरता को कम करने, आयात व्यय को कम करने और दीर्घकालिक ऊर्जा सुरक्षा को बढ़ाने के लिए एक मजबूत हरित हाइड्रोजन अवसंरचना विकसित करना महत्वपूर्ण है। निम्न तापमान वाला जल विद्युत अपघटन हरित हाइड्रोजन उत्पादन के लिए एक आशाजनक उपाय है क्योंकि यह अक्षय ऊर्जा और नाभिकीय ऊर्जा सहित विभिन्न कार्बन मुक्त बिजली स्रोतों के साथ संगत है। यह बड़े पैमाने पर परिनियोजित आवश्यक लचीलापन और स्केल-क्षमता प्रदान करते हुए उच्च-शुद्धता वाले हाइड्रोजन के कुशल उत्पादन को संभव बनाता है। चूंकि औद्योगिक विद्युत अपघटक स्टैक मुख्य रूप से आयात किए जाते हैं, इसलिए आत्मनिर्भरता प्राप्त करने के लिए स्वदेशी प्रौद्योगिकी विकसित करना आवश्यक है। भारी पानी प्रभाग, भापअ केंद्र में क्षारीय जल विद्युत अपघटक प्रौद्योगिकी को 4 NL/h से बढ़ाकर लगभग 100 Nm³/h कर दिया गया है, जिसमें 10 Nm³/h प्रौद्योगिकी को एचपीसीएल, बीपीसीएल और बीएचईएल सहित 11 उद्योगों को हस्तांतरित किया गया है। स्वदेशी केशिका, संकर प्राकृतिक परिसंचरण और पीईएम जल विद्युत अपघटक भी सफलतापूर्वक विकसित किए गए हैं।

ABSTRACT

Developing a robust green hydrogen infrastructure is of strategic significance for the nation due to the high dependency on crude oil imports. Green hydrogen provides a sustainable pathway to reduce dependence on fossil fuels and to decarbonise the key industrial sectors including refineries and steel. Low-temperature water electrolysis is one of the most promising options due to its compatibility with variable load renewable energy sources such as solar power and continuous baseload nuclear power. As industrial electrolyser stacks are currently imported, at Heavy Water Division, BARC, alkaline water electrolyser technology has been developed indigenously and scaled up from laboratory-scale with hydrogen production capacity of 4 NL/h to industrial-scale systems of nearly 100 Nm³/h. The technology of 10 Nm³/h hydrogen production has been transferred to 11 industries, including HPCL, BPCL and BHEL. In addition, advanced capillary and hybrid natural circulation electrolyzers, as well as an indigenous lab scale PEM water electrolyser stack have also been successfully developed, demonstrating comprehensive national capability in advanced hydrogen production technologies.

KEYWORDS: Green hydrogen, Alkaline Water Electrolysis (AWE)



भा.प.अ. केंद्र में परीक्षण किए जा रहे प्रोटोटाइप 0.5 MW और 1 MW क्षारीय जल विद्युत अपघटक स्टैक ढेर।

Prototype 0.5 MW and 1 MW Alkaline water electrolyser stacks under testing at BARC

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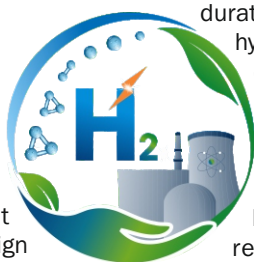


Introduction

Green hydrogen is emerging as a promising option for global decarbonization due to its potential to replace the fossil fuels in different industries including refineries, steel and fertilizer industries. Among the available hydrogen production methods, water electrolysis using renewable and nuclear energy offers a clean and sustainable route for hydrogen generation without carbon dioxide emission. The process involves electrochemical decomposition of water into oxygen and hydrogen with electricity as the source of energy. Various electrolyser technologies such as Alkaline Water Electrolysis (AWE), Proton Exchange Membrane Water Electrolysis (PEMWE), Solid Oxide Electrolysis Cells (SOEC), and Anion Exchange Membrane Water Electrolysis (AEMWE) have been explored globally with each process having specific advantages and limitations related to efficiency, operating conditions, and cost. However, large-scale deployment of electrolytic hydrogen production still faces challenges including high capital cost, catalyst and membrane durability, renewable energy intermittency, stack degradation, and lack of hydrogen storage and transportation infrastructure. Continued advancements in materials, stack design, and system integration are therefore essential for achieving the cost-effectiveness and sustainable green hydrogen production.

Low Temperature Water Electrolyser Technologies

Low-temperature water electrolyser technologies are gaining significant global attention for green hydrogen production due to their relatively simple operation and hydrogen production in a single step with high hydrogen purity at ambient conditions. The electrolysers are modular in design and its capability to work at large turn down ratio is also well known. Hence, electrolysers are considered as the most promising option for coupling with the renewable energy sources. The major low-temperature electrolyser technologies include Alkaline Water Electrolysis (AWE), Proton Exchange Membrane Water Electrolysis (PEMWE), and Anion Exchange Membrane Water Electrolysis (AEMWE). Among these, AWE is the most preferred option in terms of maturity, owing to its low cost, long operational life, and use of non-precious catalysts, although in general, it is limited from lower current density. PEMWE offers higher current density, compact system design, rapid response to fluctuating renewable power and high-pressure hydrogen production, but its deployment in industries is limited by high capital cost and dependence on expensive noble metal catalysts and membranes. AEMWE is a promising next-generation electrolyser technology that seeks to combine the benefits of conventional alkaline and PEM electrolysers by enabling the use of low-cost, non-precious metal catalysts within a compact cell architecture. However, subsequent improvements in membrane stability, ionic conductivity, and stable long-term operational performance are required before widespread commercialization. At present, alkaline and proton exchange membrane electrolysers constitute the largest share of the global installed electrolysis capacity, with their deployment accelerating in response to national hydrogen initiatives and worldwide decarbonization objectives.



Indian Scenario

In Indian context, establishing hydrogen infrastructure is critically important due to the country's large dependence on fossil fuel imports and the significant economic constraints associated with rising import bills. India imports a major portion of its fossil fuel requirement, making economy highly volatile due to the changes in oil prices globally, geopolitical conflicts, and supply chain disruptions. Therefore, critical national priorities will still remain as energy security and self-reliance. In this regard, green hydrogen offers a promising pathway for decreasing dependence on imported fossil fuels while supporting for a sustainable transition using indigenous technologies. India possesses significant potential for renewable energy generation owing to its large geographical area, high solar irradiance and extensive coastline. The country has abundant renewable energy resources that can be effectively utilized for large-scale green hydrogen production through water electrolysis. The electrolysers can be effectively integrated with both intermittent renewable energy sources such as solar as well as stable nuclear power facilitating for the production of green hydrogen without carbon emissions. Such renewable / nuclear-assisted electrolysis systems offer several advantages including reduction in greenhouse gas emissions, utilization of surplus renewable electricity, grid balancing, long-duration energy storage, and production of high-purity hydrogen without carbon emissions. Green hydrogen offers a critical role in decarbonizing several hard-to-abate industrial sectors including petroleum refining, fertilizer production, steel manufacturing, transportation, power generation, and chemical industries. Replacement of fossil-fuel-derived hydrogen with green hydrogen can substantially reduce carbon dioxide emissions and minimize environmental pollution and climate change impacts. Recognizing its strategic importance, India has launched the National Green Hydrogen Mission to promote domestic hydrogen production, electrolyser manufacturing, and supporting infrastructure development. Indigenous development of electrolyser and hydrogen technologies is expected to strengthen national energy security, reduce import dependency, support industrial growth, and accelerate the transition to a sustainable low-carbon economy.

Indigenous Alkaline Water Electrolyser Technology Development

At present, all the industrial electrolyser stacks in the country using low temperature water electrolyser technologies are imported. Indigenous development of low temperature water electrolyser technologies is critically important for achieving energy security, technological self-reliance, and large-scale deployment of green hydrogen production. Since AWE is presently the most mature and commercially viable technology for bulk hydrogen generation, development of domestic expertise in alkaline electrolyser design, stack engineering, electrode preparation, diaphragm fabrication, balance-of-plant systems, and manufacturing infrastructure can significantly reduce dependence on imported technologies and critical components. Indigenous technology development also enables cost reduction through localization



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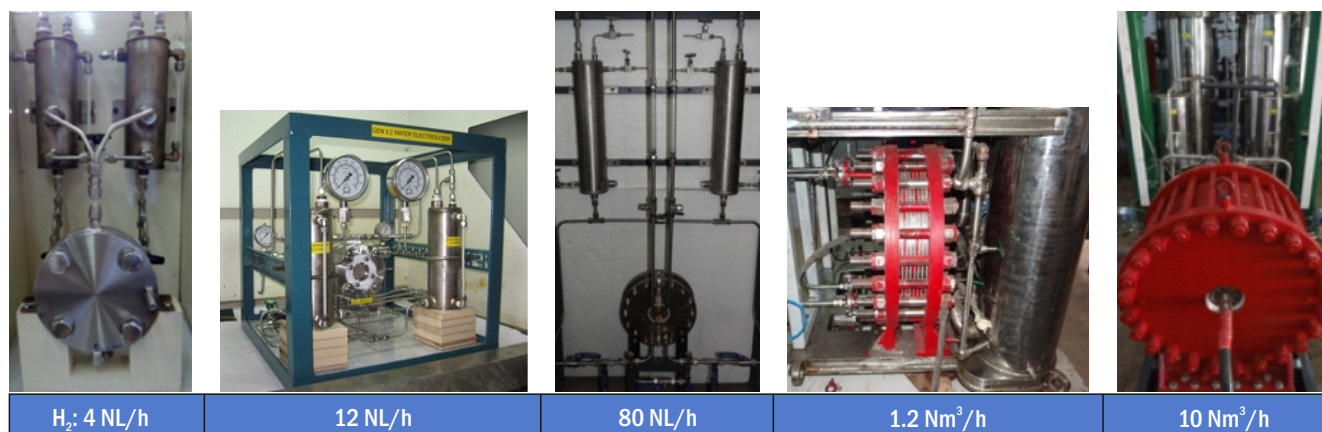


Fig.1: Different stages of development from 'lab to land'.

of materials and manufacturing, adaptation to Indian operating conditions, and creation of a robust domestic supply chain. Furthermore, it supports different industrial strategic sectors such as refineries, fertilizers, steel, heavy transport, and renewable energy storage while promoting national initiatives such as 'Make in India' and the 'National Green Hydrogen Mission'. Development of domestic alkaline electrolyser technology is also essential for enhancing long-term technological competitiveness, generating skilled employment, supporting export opportunities, and ensuring energy resilience against global supply chain disruptions and geopolitical uncertainties.

Based on the above vision, Heavy Water Division (HWD), BARC has initiated the indigenous development of both alkaline and PEM water electrolyser technologies from lab scale to industrial scale. The development of porous nickel electrodes constituted a key technological advancement in the alkaline water electrolyser development program undertaken at HWD, BARC [1]. This porous structure provides high surface area and improves electrochemical reaction rates, reduces overpotential, and increases hydrogen production efficiency. In addition, porous nickel electrodes facilitate efficient gas bubble release and mass transfer, making them highly suitable for high-current-density and large-scale alkaline water electrolysis applications. Nickel is selected as electrode material because of its favourable electrical conductivity, combined with adequate catalytic activity.

Different Developmental Stages of AWE Technology

The development of porous nickel electrode fabrication technology was initiated at the laboratory scale using electrodes of approximately 50 mm diameter. An alkaline water electrolyser stack of single cell with hydrogen production capacity of 4NL/h is designed and operated at a current density of 5000 A/m².

Subsequently, multi-cell bench-scale electrolyser systems were developed to investigate the influence of stacking configuration and electrolyte circulation on system performance. A three-cell stack electrolyser stack was fabricated and tested under similar operating conditions for hydrogen production rate of 12 NL/h. Based on the confidence gained from these studies, the electrode diameter was

progressively increased to three times for further scale-up investigations using larger two-cell stack configurations. In later stages, the electrode size was expanded up to ten times and the electrolyser modules were designed for operation at elevated pressures. A six-cell stack electrolyser capable of producing approximately 1.2 Nm³/h hydrogen was developed, with particular emphasis on electrolyte distribution and thermal management within the stack to ensure stable high current density operation. Subsequent scale-up efforts led to the development of a larger electrolyser system comprising two cell-module stacks arranged hydraulically in parallel and electrically in series, capable of producing 10 Nm³/h of hydrogen with an overall power requirement of approximately 50 kW. The integrated skid-mounted plant was also designed, which includes process systems for gas purification, pressure and flow regulation, gas-liquid separation, chilled water circulation, DC power supply and demineralized water feeding. The fully automated system is designed for continuous on-site hydrogen generation and delivery. The operation of the above plant has been carried out for more than 5000 hours. Four such units were developed and deployed at various sites. Subsequently, the indigenous alkaline water technology developed at BARC at a scale of 10 Nm³/h hydrogen production (50kW) has been transferred to 11 Indian industries. The different developmental phases from "lab to land" at HWD, BARC is shown in Fig.1.

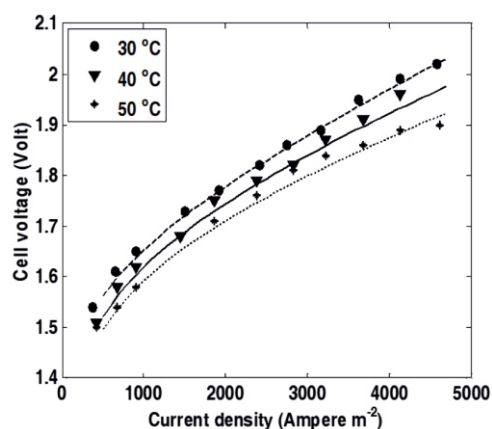


Fig.2: The polarization characteristics of the cell module stack at different temperatures [1-2].



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Table-1: Comparison of Ohmic parameter (Ωm^2) with literature [1-3].

Temperature (°C)	Ohmic parameter (Ωm^2)	
	Reported	BARC Electrolyser
30	7.3×10^{-5}	6.79×10^{-5}
40	7.05×10^{-5}	5.28×10^{-5}
50	6.8×10^{-5}	4.56×10^{-5}

Table-2: Lumped exchange current density parameter j_0 (A/m^2): Reported literature and present study [1-4].

Temperature (°C) ++	j_0 (A/m^2)	
	* Reported for Ni at 30% KOH	BARC Electrolyser
30	6.9540	12.0385
50	18.3251	43.8569
* Estimated based on the separate polarization data for anode and cathode		
++ Cathode parameters are reported in literature at 28 °C and 52 °C		

Electrochemical Performance of the Cell

The dependence of cell voltage on current density at different operating temperatures for the developed electrolyser cell module of 10 Nm³/h hydrogen generation plant is shown in Fig.2 [1-2]. The overall cell voltage is primarily influenced by Ohmic resistance and activation overpotential losses. The parameters governing different sources of performance loss can be estimated by evaluating the electrochemical polarization characteristics of the system. The Ohmic parameter, representing resistive losses within the cell, was evaluated and compared with values reported for electrolyzers available in literature (Table-1). The present indigenously developed BARC cell module exhibited comparatively lower resistance over the operating temperature range of 30–50 °C than the reported systems [3]. Compared with previously published studies, BARC developed electrolyser demonstrates reduced Ohmic resistance, indicating superior cell efficiency and overall performance. In addition, the exchange current density, which reflects electrode reaction kinetics and activation losses, was also analysed. Higher exchange current density values correspond to superior electrocatalytic activity of the electrode and lower activation overpotential. Comparison with literature data (Table-2) indicates improved electrode kinetics for the presently developed porous electrodes assembled in the cell module. Detailed electrochemical analysis is provided in Ref. [1-2]. The developed electrolyser achieved a current density of ~ 5000 A m⁻² at a cell voltage of ~1.9 V, even at a relatively low operating temperature of 50 °C compared to industrial stacks operating at >70 °C, demonstrating favourable electrochemical performance.



Fig.3: List of 50 kW Alkaline Water Electrolyzer Technology Transfer Licensees.

Industrial Collaborations

The indigenous alkaline water electrolyser technology developed at HWD, BARC, with 10 Nm³/h hydrogen production capacity, corresponding to power consumption of nearly 50kW, has been transferred to 11 Indian industries consists of leading Public Sector Units (PSU) such as BPCL, HPCL and BHEL and other key private industries including Bharat Forge, Godrej & Boyce and ThermoMax. The list of all alkaline water electrolyser technology transfer licensees is given in Fig.3 and all the licensees are at various stages of technology commercialization. HWD, BARC had also successfully incubated a 150 kW Alkaline water electrolyser technology through M/s Pratishna GreenTech, Mumbai and the developed system is shown in Fig.4. Due to the growing demand of green hydrogen, a need for scale up of the alkaline water electrolyser technology to MW scale was also initiated. HWD, BARC embarked on development of indigenous MW scale alkaline water electrolyser technology by developing 0.5 MW and 1 MW prototype stacks. The prototype stacks were tested successfully at BARC (Fig.5). Subsequently, a MoA has been formulated with BARC and BPCL for deployment of full scale 2 x 0.5 MW stacks for production of green hydrogen at the premises of Cochin International Airport (CIAL), Kochi. The full scale 0.5 MW stack was integrated with 1 MW Alkaline water electrolyser plant in collaboration with BPCL at the premises of CIAL, marking the world's first green hydrogen fuelling station in any airport premises [5]. The photograph of 0.5 MW indigenous electrolyser stack is shown in Fig.6.



Fig.4: 150 kW Alkaline water electrolyser plant developed under incubation.



Fig.5: Prototype 0.5 MW and 1 MW Alkaline water electrolyser stacks under testing at BARC.

Development of advanced passive alkaline water electrolyser stacks

Development of advanced passive alkaline water electrolyser stacks operating without external pumps for electrolyte recirculation are highly important for developing simple, rugged, energy-efficient and reliable hydrogen generation systems. In such systems, electrolyte circulation occurs naturally through density differences generated by gas evolution and temperature gradients within the electrolyser or by capillary forces, thereby eliminating the need for mechanical pumping systems. This significantly reduces auxiliary power consumption, maintenance requirements, operational complexity, and overall system cost. The absence of moving components also improves long-term reliability, minimizes vibration and leakage issues, and enhances safety during continuous operation. In addition, passive circulation systems offer compact design, lower balance-of-plant requirements and easier scalability, making them particularly attractive for decentralized and renewable energy-based green hydrogen production applications.

In HWD, BARC, the both the development of capillary electrolyser stack and natural circulation electrolyser stacks were also taken up. The capillary electrolyser represents an advanced alkaline water electrolysis technology capable of producing high-purity hydrogen and oxygen directly within the cell stack. As a result, it significantly reduces or eliminates the need for auxiliary Balance of Plant (BOP) systems that are



Fig.6: Indigenous 0.5 MW alkaline water electrolyser stack integrated with BOP in collaboration with BPCL at the premises of CIAL, Kochi.

conventionally employed for gas purification and conditioning. In capillary electrolysers, porous separator materials utilize capillary forces to sustain a thin electrolyte film on the electrode surface, facilitating electrochemical operation with minimal electrolyte inventory. A continuous supply of water is maintained at the electrochemically active sites, while the generated hydrogen and oxygen are efficiently evolved from the system, limiting gas bubble hold up and mitigating mass transfer limitations. Consequently, the design lowers Ohmic resistance, enhances the effective utilization of electrode surfaces, and supports energy-efficient hydrogen generation at elevated current densities. In this system, all the process components, except power supply and control system, are inbuilt in the cell module itself. A 10-cell stack of capillary electrolyser system is designed, fabricated and performance evaluation has been carried out meeting the design parameters. The photograph of 10 cell capillary scaled up stack is given in Fig.7.

In a natural circulation electrolyser, electrolyte circulation occurs due to density differences created by the evolution of hydrogen and oxygen gas bubbles during electrolysis. The gas-liquid mixture formed inside the cell rises upward, while comparatively denser electrolyte flows downward, establishing continuous circulation without the need for external pumps. This passive circulation mechanism improves heat removal, maintains electrolyte mixing, and reduces auxiliary power consumption and system complexity. The gas- liquid separator is provided as a part of internal construction feature in each half cell of the stack. A single cell stack of hybrid natural circulation electrolyser system (Fig.8) is



Fig. 7: Scaled up 10 Cell capillary electrolyser stack.



Fig.8: Hybrid natural circulation electrolyser stack under operation.



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Fig.9: Indegenous PEM cell stack and PEM based laboratory hydrogen generator.

designed, installed and tested at a current density of 3000 A/m² with hydrogen production rate of ~40 NL/h while achieving a hydrogen purity of more than 99.9%. Further, a 10 cell stack has been designed and fabricated for 500 NL/h hydrogen gas production capacity.

PEM Water Electrolyser Technology Development

PEM water electrolyzers rely on ion-conducting polymer membranes and noble metal catalysts to efficiently drive electrochemical reactions. Noble metal catalysts are commonly utilized because of their excellent catalytic activity and long-term operational stability. A key advantage of this technology is its capability to produce high-purity, pressurized hydrogen directly from the electrolyser, thereby reducing the requirement for additional gas compression units. However, the dependence on expensive noble metals and specialized membrane materials can increase the overall system cost. In addition, PEM systems generally require highly purified water and careful operating conditions to maintain membrane durability and consistent performance over extended periods.

In alignment with the “Make in India” initiative and the goal of developing indigenous hydrogen generation technologies, HWD, BARC has successfully designed and fabricated a Membrane Electrode Assembly (MEA) based on Perfluoro-sulfonic acid (PFSA) membranes for PEM water electrolysis applications. The developed MEA was integrated into an in-house engineered electrolyser cell body, where it demonstrated stable operation at a current density of 10,000 A/m² with an operating voltage of approximately 1.9 V, exhibiting performance comparable to commercially available imported PEM electrolyzers. During the course of development, several technical challenges related to membrane-electrode integration, catalyst utilization, interfacial contact resistance, sealing integrity, and stable operation under high current density conditions were addressed through optimization of fabrication protocols and cell design. Particular emphasis was placed on achieving improved proton transport, uniform catalyst distribution, and enhanced mechanical stability to ensure reliable long-term operation. Subsequent evaluation of the fabricated PEM water electrolyzer single cell at room temperature, sustained and reliable operation for more than 1200 hours is carried out, delivering hydrogen at a rate of 10 NL/h with a dry basis purity of 99.99%. Subsequently an indigenous laboratory PEM based hydrogen generator with capacity of 18 NL/h is developed and completed operational trial runs of 500 hours. The photograph

of the system is shown in Fig.9. Building upon these successful demonstrations, ongoing efforts are focused on scaling up the system to a hydrogen generation capacity of 500 NL/h while further improving efficiency, durability, and operational reliability.

Conclusion

Low-temperature water electrolyser technologies play a major role in the large-scale generation of green hydrogen due to their operational simplicity, modular scale up and compatibility with renewable energy sources. Significant progress has been achieved at HWD, BARC through the indigenous development and scale-up of alkaline water electrolyzers, beginning from laboratory-scale of 4 NL/h hydrogen production capacity to industrial-scale systems of approximately 1 MW capacity (200 Nm³/hr). Performance evaluation of the developed electrolyser 50 kW stacks indicated superior electrochemical characteristics compared to reported literature data. Four such electrolyser plants of 10 Nm³/h capacity were successfully operated continuously for over 5000 hours and subsequently installed at user locations for field operation. The successful demonstration of the technology led to its commercialization through transfer to 11 industrial partners, including leading PSUs such as HPCL, BPCL and BHEL. In addition to conventional alkaline electrolyzers, advanced concepts such as capillary electrolyzers and hybrid natural circulation electrolyzers have also been developed to reduce auxiliary power consumption, and simplify system design with better energy efficiency. Furthermore, an indigenous PEM water electrolyser stack with a hydrogen generation capacity of 18 NL/h has been successfully developed, demonstrating the capability in advanced PEM water electrolyser technologies. These developments establish strong technological competence at BARC in electrolyser design, stack engineering, and hydrogen production systems, contributing significantly toward self-reliance and the advancement of the green hydrogen economy.

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