

Hydrogen Production Using Nuclear Energy

A Pathway to Clean Energy Through Thermochemical and Electrochemical Processes, Integrating Nuclear Power with Hydrogen Generation Technologies

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SUMMARY

- **Promising Energy Pathway:** Hydrogen production using nuclear energy offers a scalable, low-carbon solution for future energy systems.
- **Integrated Approach:** The paper examines how nuclear power can supply both electricity and high-temperature heat for hydrogen production.
- **Technological Focus:** It explores electrolysis and thermochemical water splitting methods, evaluates Generation IV reactor technologies, and analyzes their suitability.
- **Applications and Challenges:** Key findings address hydrogen’s role in transportation, industry, and energy storage, while considering economic feasibility, infrastructure requirements, and public perception.

1. INTRODUCTION

Hydrogen production using nuclear energy encompasses multiple pathways that align with global energy and climate goals. These include hydrogen fuel for transportation and industrial applications such as steelmaking and ammonia synthesis, energy storage by converting surplus nuclear electricity into hydrogen for later reconversion to electricity, and export potential where countries like Japan and South Korea are exploring the import of clean hydrogen produced via nuclear energy [14] [15]. This paper explores these applications in depth and evaluates the technologies—electrolysis and thermochemical water splitting—that enable hydrogen generation when integrated with nuclear power.

- **Hydrogen Fuel:** For transportation and industrial applications (e.g., steelmaking, ammonia synthesis, sustainable aviation fuel (SAF) and/or methanol).
- **Energy Storage:** Convert nuclear energy into hydrogen for storage and reconversion to electricity.
- **Export Potential:** Countries like Japan and South Korea are exploring the import of clean hydrogen produced via nuclear energy.

Recent national and international strategies underscore the growing momentum behind clean hydrogen development. The UK Hydrogen Strategy (2021) outlines a roadmap to produce 5 GW of low-carbon hydrogen by 2030, emphasizing nuclear as a potential contributor to clean hydrogen supply. Similarly, global initiatives such as the EU Hydrogen Strategy, Japan’s Basic Hydrogen Strategy, and the U.S. Hydrogen Shot reflect a coordinated international push toward hydrogen as a cornerstone of future energy systems. These efforts align with broader decarbonization goals and highlight the strategic role of nuclear energy in enabling scalable, low-carbon hydrogen production.

Figure 1 presents the current global distribution of hydrogen production methods. Natural gas reforming remains the predominant source, followed by coal gasification. Although electrolysis and other emerging technologies currently represent a small share, they offer promising opportunities for cleaner and more sustainable hydrogen production as innovation and investment in low-carbon methods continue to grow. [1]

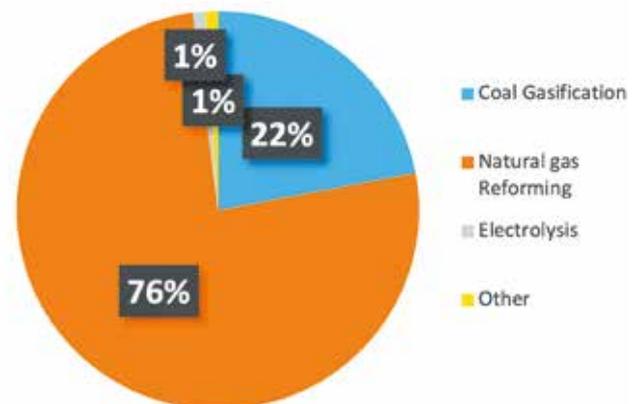


Figure 1: Global Hydrogen Production Methods

This bar chart in Figure 2 compares the estimated costs of hydrogen production across various methods, including nuclear-based options. [2]

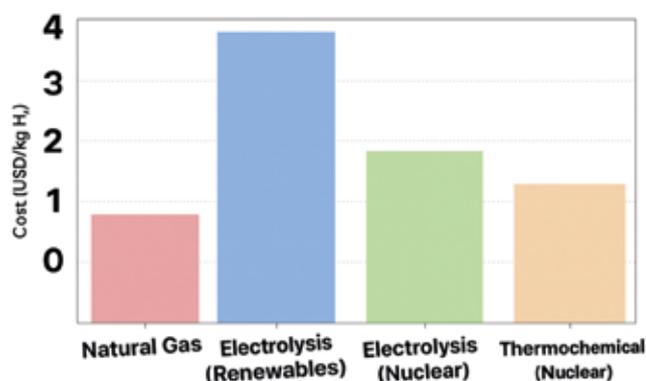


Figure 2: Hydrogen Production Costs by Method

Coupling hydrogen production with nuclear energy presents a promising pathway to reduce the overall cost of hydrogen, leveraging the stable and low-carbon energy supply from nuclear sources.

1.1 Electrolysis Using Nuclear Electricity

Electricity generated by nuclear power plants can be used to split water into hydrogen and oxygen. Key electrolysis technologies include:

- Alkaline Electrolysis
- PEM (Proton Exchange Membrane) Electrolysis
- High-Temperature Electrolysis (HTE)

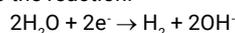
While nuclear energy may appear less economically attractive on a strictly LCOE basis, its unique attributes can make it a valuable asset for electricity-only electrolysis. Nuclear power offers unmatched reliability and baseload generation, which is crucial for continuous hydrogen production without the intermittency challenges faced by renewables. Additionally, nuclear plants can operate at high-capacity factors, ensuring consistent energy supply that aligns well with the operational needs of electrolysis systems. In regions with limited renewable potential or constrained land availability, nuclear energy can provide a low-carbon alternative that supports decarbonization goals. Furthermore, policy incentives, long-term energy security considerations, and the potential integration of advanced nuclear technologies (e.g., small modular reactors) may shift the economic calculus in favor of nuclear, especially when hydrogen is viewed as a strategic energy vector.

1.1.1. Alkaline Electrolysis

Alkaline electrolysis is one of the most mature and widely used methods for hydrogen production through water splitting. It operates by passing an electric current through an aqueous alkaline solution—typically potassium hydroxide (KOH) or sodium hydroxide (NaOH)—to decompose water into hydrogen and oxygen.

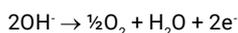
Reactions

In this electrochemical process, at the cathode (-), water is reduced according to the reaction:



This reaction produces hydrogen gas and hydroxide ions.

At the anode (+), the hydroxide ions are oxidized through the reaction:



This results in the release of oxygen gas, water, and electrons.

These reactions are typical of alkaline water electrolysis, where an alkaline electrolyte (such as potassium hydroxide) facilitates the transport of hydroxide ions between electrodes.

Advantages

Alkaline electrolysis offers several advantages that make it a viable option for hydrogen production. It is a proven technology that is commercially available and well-understood, providing confidence in its reliability and performance. Compared to other methods such as PEM and solid oxide electrolysis, it has relatively low stack costs, which contributes to its accessibility for large-scale deployment. However, overall system cost remains dependent on specific design choices, including balance-of-plant components, integration strategies, and operational requirements. The system is known for its durability, with a long operational life and stable performance over time. Additionally, alkaline electrolysis is highly scalable, making it suitable for meeting the demands of large-scale hydrogen production.[6]

Limitations

Despite its advantages, alkaline electrolysis has several limitations. One of the primary drawbacks is its lower current density compared to PEM electrolysis, which results in larger system footprints and reduced space efficiency. Additionally, its slower dynamic response makes it less suitable for integration with variable power sources such as solar or wind energy. The hydrogen produced may also require further purification to meet high-purity standards, adding complexity to the process. Furthermore, the use of a caustic electrolyte demands robust materials and regular maintenance to ensure long-term reliability and safety. If the electrolysis stack operates at low output pressure, additional compression equipment may be required to prepare hydrogen for storage or distribution, which can increase system complexity and cost.

Integration with Nuclear Energy

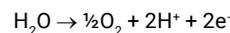
Alkaline electrolysis can be effectively powered by the steady, baseload electricity output from nuclear power plants. While it does not utilize heat input like HTE or thermochemical cycles, its compatibility with nuclear-generated electricity makes it a viable near-term option for clean hydrogen production.

1.1.2. PEM (Proton Exchange Membrane) Electrolysis

Proton Exchange Membrane (PEM) electrolysis is a modern and highly efficient method for producing hydrogen through water electrolysis. It uses a solid polymer electrolyte that conducts protons from the anode to the cathode while separating the product gases.

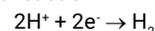
Reactions:

At the anode (+), water undergoes oxidation according to the following reaction:



This process releases oxygen gas, protons, and electrons.

At the cathode (-), the protons and electrons recombine to form hydrogen gas through the reaction:



Together, these reactions describe the fundamental electrochemical processes occurring in a typical water electrolysis cell.

Advantages

This system offers several key advantages. It delivers high efficiency, particularly at partial loads, which makes it well-suited for dynamic operation. Its compact design and reduced system complexity (i.e. PEM does not use alkaline electrolyte or need a gas scrubber) results in a smaller footprint compared to traditional alkaline systems, allowing for easier integration into various setups. The system also produces pressurized high-purity hydrogen, making it ideal for use in fuel cells and a range of industrial applications. Additionally, it features a fast response and start up time, which enables seamless integration with intermittent renewable energy sources such as solar and wind power. [7]

Challenges

Despite its advantages, the system faces several challenges. One major issue is the high cost, primarily due to the use of platinum group metals on catalysts and specialized membrane materials. Additionally, it requires high water purity, specifically deionized water, to prevent degradation of the membrane and ensure long-term performance, which can increase the system complexity and cost. Another concern is durability, as both the membrane and the catalysts degrade over time, which may negatively impact the system's efficiency and reliability.

Integration with Nuclear Energy

PEM electrolysis is a modern method for producing hydrogen that offers operational flexibility and high responsiveness, particularly under variable load conditions. While its efficiency is comparable to that of alkaline electrolysis and lower than high-temperature electrolysis, its compact design and ability to produce high-purity hydrogen under pressure make it well-suited for modular and dynamic applications.

1.1.3. Solid Oxide Electrolysis (SOEC)

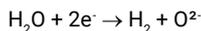
High-Temperature Electrolysis through Solid Oxide Electrolysis Cell (SOEC) offers higher efficiency when coupled with high-temperature nuclear reactors (600–850°C).

High-Temperature Electrolysis (HTE) is an advanced and highly efficient method of hydrogen production that leverages both electricity and high-temperature heat—making it particularly well-suited for integration with nuclear reactors.

Reactions:

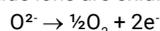
In this configuration, the electrochemical reactions proceed as follows:

At the cathode (-), water is reduced according to the reaction:



This reaction produces hydrogen gas and oxide ions.

At the anode (+), the oxide ions are oxidized through the reaction:



This results in the release of oxygen gas and electrons.

Together, these reactions describe the operation of a system such as a SOEC, where oxygen ions are transported through a solid electrolyte.

The oxygen ions (O^{2-}) travel through a solid ceramic electrolyte (typically yttria-stabilized zirconia), while hydrogen is collected at the cathode.

Advantages

SOECs offers several advantages, including no use of platinum group metals (PGMs). One of the most significant benefits is its higher efficiency, which can reach 50–60% based on electrical-to-hydrogen conversion alone, and up to 80–90% when integrated with high-temperature heat sources, as shown in Table 1. This higher efficiency is achieved by replacing a portion of the electrical energy input with thermal energy, which is particularly advantageous when coupled with advanced nuclear reactors capable of supplying both electricity and high-grade heat. Importantly, HTE is also applicable to current-generation water-based reactors, although with lower efficiency, since they provide moderate-temperature heat that can still contribute to the process. A heat exchanger can be used to generate steam for the Solid Oxide Electrolyser Cell (SOEC), effectively decoupling the reactor coolant loop from the electrolyser system. This design feature is particularly valuable in advanced configurations that recover and reuse waste heat from various sources, including industrial processes. Additionally, HTE systems benefit from reduced electricity demand, as a portion of the required energy input is replaced by heat, thereby lowering operational costs in environments where thermal energy is readily available. [5]

Challenges

SOEC also presents several challenges. One of the primary concerns is material durability, as the high operating temperatures demand advanced materials capable of withstanding significant thermal stress and chemical degradation over time. The system complexity is another challenge, requiring precise thermal management and seamless integration with external heat sources to maintain optimal performance. Additionally, the technology maturity level remains lower than PEM or Alkaline systems. SOEC is still in early adoption phase and has not yet reached widespread commercialization. Furthermore, H_2 produced needs to be dried and compressed to meet purity and pressure requirements for downstream applications. Improved durability and reduced leveled costs are essential to make SOEC systems economically viable for large-scale deployment.

Integration with Nuclear Energy

Like PEM and alkaline electrolysis (ALK) systems, SOEC is compatible with nuclear reactors that can provide both electricity and heat. However, high-temperature reactors are specifically required for thermochemical cycles due to their ability to deliver the elevated temperatures needed for those processes.

1.2. Thermochemical Water Splitting

This method uses heat from advanced nuclear reactors to drive chemical reactions that split water molecules. Prominent examples are Sulfur-Iodine (S-I) and Calcium-Bromide (Ca-Br) Cycles. Two of the most significant benefits are its higher efficiency and the fact that it does not require platinum group metals (PGMs), which reduces material costs and supply chain constraints.

Advantages:

This system offers unique benefits, particularly in high-temperature environments. One key advantage is that it requires only heat, not electricity, making it highly efficient in settings where thermal energy is abundant. It is especially suitable for high-temperature reactors,

typically operating above 800°C, which makes it an ideal candidate for integration with advanced nuclear or industrial heat sources.

Challenges:

This approach also comes with notable challenges. It involves complex chemical engineering, requiring precise control over reaction conditions and system design. Additionally, it demands advanced materials capable of withstanding extreme temperatures and harsh chemical environments, which can increase both cost and technical difficulty. A further impediment to adoption is the lack of commercially available reactors capable of delivering temperatures above 800°C, making implementation even more challenging.

1.3 Suitable Reactor Technologies

To support high-efficiency hydrogen production, the following Generation IV reactors are particularly promising: [8]

- High-Temperature Gas-Cooled Reactors (HTGRs)
- Molten Salt Reactors (MSRs)
- Sodium-cooled Fast Reactors (SFRs) or Lead-cooled Fast Reactors (LFRs)

While these reactors are designed for enhanced thermal efficiency, they are not currently used for hydrogen production. However, their ability to deliver high-temperature heat may offer future potential for integration with hydrogen generation systems.

1.3.1. Heat Integration Opportunities and Challenges

Although the integration of electricity from nuclear power into hydrogen production is well-established, the use of nuclear-generated heat presents additional opportunities for improving system efficiency. Generation IV nuclear reactors—specifically High-Temperature Gas-Cooled Reactors (HTGRs), Molten Salt Reactors (MSRs), and Very High Temperature Reactors (VHTRs)—are uniquely capable of delivering the high-temperature heat required for thermochemical cycles, and could enhance the efficiency of high-temperature electrolysis (HTE). While HTE can be carried out using low-grade heat from conventional Light Water Reactors (LWRs), access to higher-temperature heat from advanced reactors can improve overall system performance, which leverages both forms of energy to achieve efficiencies as high as 80–90%, and thermochemical cycles like the sulfur-iodine or calcium-bromide processes, which require temperatures above 800°C.

However, integrating heat into hydrogen production systems introduces several challenges. Effective thermal management is essential to maintain optimal operating conditions, and the high temperatures involved demand the use of advanced materials capable of withstanding significant thermal stress and chemical degradation. Additionally, the complexity of systems that combine heat and electricity requires robust engineering and control strategies to ensure safe and reliable operation.

1.3.2. Co-location Strategies: Inside vs. Outside the Nuclear Fence

The physical placement of hydrogen production facilities relative to the nuclear plant—whether inside or outside the security fence—has important implications for safety, regulatory compliance, and infrastructure design. Locating hydrogen systems inside the fence can offer advantages such as shared infrastructure, reduced transmission losses, and centralized operational control.

However, this approach also requires the hydrogen facility to meet nuclear-grade safety and security standards, which can increase regulatory complexity.

Conversely, placing hydrogen production facilities outside the nuclear fence allows for more conventional industrial standards and potentially simpler permitting processes. This strategy provides greater flexibility in design and operation but may necessitate additional infrastructure for the secure and efficient transfer of heat and electricity. It can also introduce new considerations for emergency planning and perimeter security. The decision between inside- and outside-fence co-location depends on factors such as site footprint, jurisdictional boundaries, and integration costs.

The co-location of hydrogen production systems with nuclear facilities introduces important policy and regulatory considerations. When hydrogen systems are placed inside the nuclear security fence, they fall under nuclear regulatory jurisdiction, requiring compliance with stringent safety, security, and licensing standards. This can increase complexity but may streamline infrastructure sharing and operational oversight. Conversely, locating hydrogen systems outside the fence may allow for industrial-grade licensing, reducing regulatory burden but necessitating robust interfaces for heat and electricity transfer. These decisions affect not only the licensing pathway but also emergency planning, environmental assessments, and stakeholder engagement, making early coordination with regulators essential. National frameworks - such as those in Canada, the U.S., and the UK - are evolving to support hybrid energy systems, but clear guidance on boundary conditions and licensing integration remains a critical enabler for deployment.

1.3.3. External Risk Factors: Hydrogen Explosion and Nuclear Safety Basis

Hydrogen's flammability and explosion potential introduce external hazards that must be carefully evaluated within the nuclear safety basis. Large-scale hydrogen production and storage near nuclear facilities requires comprehensive risk assessments that consider scenarios such as blast overpressure, fire propagation, and gas release. These risks must be mitigated through thoughtful design strategies, including physical separation of systems, the use of blast walls and venting mechanisms, and the implementation of leak detection and emergency shutdown systems. Furthermore, hydrogen-related hazard scenarios should be incorporated into the plant's Probabilistic Safety Assessment to ensure a holistic approach to safety.

1.3.4. Impact of Process Heat Temperature on Electrolysis Efficiency and Technology Selection

The temperature of process heat plays a critical role in determining the efficiency and suitability of different electrolysis technologies. Low-temperature electrolysis methods such as alkaline and PEM electrolysis typically operate within the range of 50°C to 80°C. These technologies rely primarily on electricity and do not benefit significantly from thermal energy, making them compatible with conventional nuclear reactors that supply steady electrical output but limited high-grade heat. In contrast, high-temperature electrolysis (HTE) systems, particularly those using solid oxide electrolysis cells (SOECs), operate at elevated

temperatures between 600°C and 850°C at the cell. A substantial portion of the energy required for water splitting is provided as heat, which reduces the electrical energy demand while improving the overall system efficiency. For Solid Oxide Electrolysis Cells (SOECs), steam is supplied as an input at approximately 5 to 10 barg, in a saturated state, with a temperature range of 150°C to 170°C. This represents the only external heat requirement, making it a low-grade heat input. The steam can be sourced from steam turbines or other suitable tap points within the nuclear system.

The SOEC operates at its thermoneutral point, where the electrical energy supplied to the cell generates sufficient internal heat to raise the operating temperature to approximately 500°C to 600°C. This self-heating capability minimizes the need for additional thermal input beyond the initial steam supply. It is important to clarify that most of the external energy input for SOEC systems is required at relatively low temperatures - typically just above 100 °C - to vaporize the feed water into steam. This low-grade heat can be sourced from the lower end of the nuclear thermal cycle, such as turbine extraction points. However, when higher-temperature steam (e.g., >600 °C) is available - such as from advanced high-temperature reactors - it can slightly improve system efficiency by reducing the electrical energy required for

electrolysis. As noted in the literature, including a study published in the Nuclear Energy and Engineering Applications journal (UKSCIP, 2023), “most of the external energy input is only needed at relatively low temperatures >100 °C to vaporise the feed steam. When high temperature (>600 °C) steam is available this improves system efficiencies slightly.” Other sources in the literature support this observation.

Generation IV nuclear reactors - specifically High-Temperature Gas-Cooled Reactors (HTGRs), Molten Salt Reactors (MSRs), and Very High Temperature Reactors (VHTRs) - are uniquely capable of delivering the high-temperature heat required for efficient hydrogen production via thermochemical cycles and high-temperature electrolysis (HTE). Their integration into hydrogen production systems represents a strategic shift toward low-carbon, scalable solutions that could significantly alter the cost and environmental footprint illustrated in the preceding figures.

By linking the economic and technological realities shown in the graphics with the capabilities of next-generation reactors, this section emphasizes the transformative potential of nuclear energy in reshaping the hydrogen economy.

The Table 1 represents the costs of Hydrogen production by methods. [3]

Table 1: Comparative Analysis of Hydrogen Production Methods

| Characteristic | Alkaline Electrolysis | PEM Electrolysis | High-Temperature Electrolysis (HTE) | Sulfur-Iodine (S-I) | Calcium-Bromine (Ca-Br) |
|-------------------------------|--|---|---|--|---|
| Electrolyte Type | Liquid alkaline (KOH or NaOH) | Solid polymer membrane | Solid oxide ceramic | None | None |
| Operating Temperature | 60–80°C | 50–80°C | 600–850°C | >800°C | >800°C |
| Efficiency (Please see notes) | ~60–70% | ~60–70% | ~80–90% (with heat integration) | 40–50% | 35–45% |
| Hydrogen Purity | Moderate | High | High | High | High |
| Startup Time | Slow | Fast | Slow | Moderate | Moderate |
| System Complexity | Low | Moderate | High | High | High |
| Capital Cost | Lower | High | High | Very High | Very High |
| Durability / Lifetime | Long | Long | Moderate (material degradation) | Short-Moderate | Short-Moderate |
| Scalability | Good for large-scale | Good for small/medium-scale | Currently limited. Potential for medium/large scale. | Good for large scale. | Currently limited |
| Use of Precious Metals | No | Yes (e.g., platinum, iridium) | No | No | No |
| Heat Source Requirement | None | None | Requires external low-grade heat source to generate steam | High-temperature heat | High-temperature heat |
| Commercial Maturity | Mature technology | Commercially available | Emerging / under development | Low | Low |
| Water Requirement | Deionized or distilled | Ultrapure water | High purity steam (H ₂ O vapor) | Moderate | Moderate |
| Advantages | - Low cost - Mature - Simple design | - High purity - Compact - Responsive | - Very high efficiency - Heat recovery - Lower electricity demand | Requires only heat Suitable for advanced reactors | Efficient in high-temperature environments |
| Disadvantages | - Lower purity - Bulky - Slow response | - Expensive materials - Sensitive to water | - Complex - Costly - Limited deployment | Complex chemical engineering Material durability | Limited reactor compatibility Engineering complexity |

1.3.5. Technology Readiness and International Development Efforts

While thermochemical cycles such as Sulfur-Iodine (S-I) and Calcium-Bromine (Ca-Br) offer promising efficiency gains, their Technology Readiness Level (TRL) remains relatively low - typically in the TRL 3–4 range, indicating laboratory validation and early-stage prototyping. These methods require further development before reaching pilot or commercial deployment. In contrast, electrolysis technologies like alkaline and PEM electrolysis are at TRL 8–9, with widespread commercial availability.

Several Generation IV reactor designs are being actively advanced under IAEA and OECD NEA programmes to support high-temperature hydrogen production. Notably:

- The IAEA's Nuclear Hydrogen Initiative and Coordinated Research Projects (CRPs) focus on coupling high-temperature reactors with hydrogen systems.
- The OECD NEA's Technology Roadmap for Nuclear Energy and Hydrogen highlights HTGRs, VHTRs, and MSRs as key candidates for thermochemical integration.
- Countries such as Japan and South Korea are pursuing demonstration projects using HTGRs for hydrogen production, with support from these international frameworks.

These efforts aim to raise the TRL of thermochemical hydrogen production by integrating advanced reactor designs into pilot-scale systems, paving the way for future commercialization.

1.4 Applications and Potential

Hydrogen produced from nuclear energy has diverse applications. It can be used as a clean fuel for transportation and industrial processes. It also enables energy storage by converting surplus nuclear electricity into hydrogen, which can be reconverted when needed. Furthermore, there is growing interest in exporting nuclear-derived hydrogen to countries seeking low-carbon energy imports. [9]

A complete hydrogen generation and storage system integrated with nuclear energy consists of several key components:

- 1 **Hydrogen Generation Unit:** This includes electrolysis equipment such as alkaline, PEM, or high-temperature electrolysis cells. These units are powered by electricity and/or heat from nuclear reactors.
- 2 **Water Supply and Purification:** A system to deliver high-purity water (deionized or ultrapure) to the electrolysis units.
- 3 **Gas Separation, Drying and Purification:** After electrolysis, hydrogen and oxygen gases are separated. Hydrogen is dried and purified to meet storage or fuel standards.
- 4 **Compression System:** Hydrogen is compressed to reduce volume for storage. Compressors may operate at pressures ranging from 200 to 700 bar depending on the storage method or offtake route (e.g. tube trailer filling).
- 5 **Storage Infrastructure:**
 - High-Pressure Tanks: Typically made of composite materials, used for short-term or mobile storage.
 - Cryogenic Tanks: Store hydrogen as a liquid at -253°C, suitable for high-density storage but energy-intensive.
 - Underground Caverns: Salt caverns or depleted natural gas fields offer large-scale, long-term storage options.
- 6 **Control and Safety Systems:** Includes sensors, valves, and automated controls to monitor pressure, temperature, and gas

purity. Safety systems ensure leak detection and emergency shutdown.

- 7 **Distribution Interface:** Hydrogen is transferred to pipelines, fueling stations, or chemical plants depending on the application.

This integrated system enables continuous hydrogen production using nuclear baseload energy, with flexible storage options tailored to scale, cost, and end-use requirements.

Hydrogen Reconversion to Electricity:

Reconversion to electricity refers to the process of using hydrogen - produced through nuclear-powered electrolysis or thermochemical methods - as an energy carrier that can later be converted back into electrical power. In this context, hydrogen serves as a form of energy storage. When nuclear plants generate excess electricity, particularly during periods of low grid demand, that energy can be used to produce hydrogen. This hydrogen can then be stored and later reconverted into electricity when demand rises or when renewable sources are unavailable.

The reconversion typically occurs through technologies such as fuel cells or hydrogen-capable turbines. Fuel cells, for example, can generate electricity by combining hydrogen with oxygen in an electrochemical reaction, producing water as the only byproduct. Alternatively, hydrogen can be combusted in turbines to generate electricity in a more conventional manner.

This approach offers flexibility and resilience to the energy system, allowing nuclear energy to support not only continuous baseload power but also dynamic grid balancing. However, it comes with trade-offs. The round-trip efficiency - meaning the total energy retained from the initial electricity used to produce hydrogen and then reconverted - is relatively low, often around 30 to 40 percent. This is significantly lower than other energy storage technologies such as lithium-ion batteries, which typically achieve round-trip efficiencies of 85–95%, and pumped hydro storage, which ranges from 70–85%. However, hydrogen offers advantages in long-duration storage and seasonal energy shifting, where batteries and pumped hydro may be less practical or scalable. Additionally, the infrastructure required for hydrogen storage, handling, and reconversion is still developing and can be costly.

Despite these challenges, reconverting to electricity remains a promising strategy for integrating nuclear energy into a broader, more adaptable clean energy system - particularly when addressing long-duration energy storage needs and enabling sector coupling.

The biggest challenges are likely to be ensuring that the safety case remains unaffected or managing the regulatory implications if it is impacted. Additionally, careful planning of the steam system is essential to enable integration of heat sources - this is certainly feasible but must be addressed early in the design process.

2. NUCLEAR ENERGY IN ACTION-HYDROGEN PRODUCTION DEMONSTRATIONS

The diagram in Figure 3 is representing the process of hydrogen production using nuclear energy: [4]

- It illustrates how nuclear reactors provide heat for high-temperature electrolysis or thermochemical water-splitting.
- The process includes water input, nuclear heat generation, hydrogen separation, and storage.

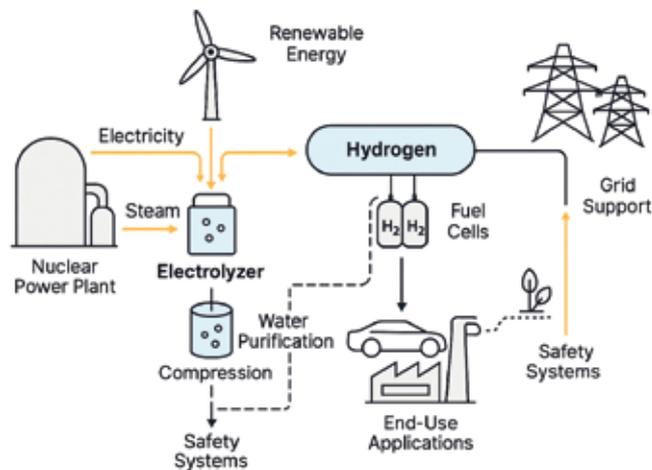


Figure 3: Hydrogen Production Diagrams

The Nine Mile Point Nuclear Power Station in Oswego, New York, is the first nuclear-powered clean hydrogen production facility in the U.S.. Supported by the U.S. Department of Energy, the project uses low-temperature electrolysis powered directly by the nuclear plant to produce hydrogen. Initially, the hydrogen is used to help cool the plant, but future plans include powering a fuel cell and supplying additional electricity to the grid.

In the United Kingdom, several initiatives are exploring the integration of nuclear energy with hydrogen production. The HINETZ (Hydrogen Integration with Nuclear Energy for Zero-carbon Technologies) programme is investigating pathways to couple nuclear power with hydrogen systems, including thermochemical and electrochemical methods. Additionally, conceptual projects at Sizewell C and Heysham are evaluating the feasibility of producing pink hydrogen - hydrogen generated using nuclear electricity - either for local industrial use or grid support. These efforts reflect the UK's broader commitment under its Hydrogen Strategy to scale up low-carbon hydrogen production and leverage existing nuclear infrastructure for clean energy transitions.

Technical Challenges:

Electrolyzer Integration: Efficient operation of low-temperature electrolysis systems with nuclear power requires precise control and compatibility with plant dynamics.

Heat Utilization: While current efforts focus on electrical input, future scaling may explore high-temperature steam electrolysis (HTSE), necessitating advanced materials and thermal management strategies.

Safety and Licensing: Incorporating hydrogen systems into nuclear facilities introduces additional safety and regulatory complexities.

Infrastructure and Scalability:

Initial Use: Hydrogen is currently used for plant cooling, minimizing infrastructure requirements.

Expansion Potential: Future applications - including fuel cells and grid support - will require new pipelines, storage, and distribution systems. The model is replicable at other nuclear sites, particularly those with excess capacity or flexible load-following capabilities.

Policy and Public Perception:

Regulatory Momentum: Federal and state incentives (e.g., tax credits, hydrogen hubs) are accelerating clean hydrogen adoption. **Public Trust:** Pairing nuclear energy with hydrogen production may improve public perception when framed as a climate-forward solution.

Note: Specific project demonstrations and U.S. Department of Energy support are detailed in the following section on Key Demonstration Projects.

Overall, while electrolysis systems are relatively mature, thermochemical cycles and high-temperature integration remain in development. Continued investment, research, and policy support are essential to overcome these barriers and realize the full potential of nuclear hydrogen production.

Key Demonstration Projects:

Hydrogen production using nuclear energy has moved beyond theoretical research and is now being actively demonstrated through several pilot projects in the United States:

Project name: Nine Mile Point Nuclear Power Station (Oswego, NY, USA)

- **Technology Used:** Low-temperature electrolysis.
- **Status:** Began producing hydrogen in February 2023.
- **Purpose:** Hydrogen is used to help cool the plant; future plans include powering a fuel cell and supplying additional electricity to the grid by 2025.

Project Name: Palo Verde Generating Station (Arizona, USA)

- **Technology Used:** High-temperature steam electrolysis (planned).
- **Partners:** Arizona Public Service (APS), DOE.
- **Goal:** Demonstrate hydrogen production using excess electricity from the plant.
- **Use Case:** Hydrogen could be used for energy storage or industrial applications

Project name: Davis-Besse Nuclear Power Station (Ohio, USA)

- **Technology Used:** Electrolysis.
- **Partners:** Energy Harbor, DOE.
- **Purpose:** Produce hydrogen for commercial sale and internal use.
- **Timeline:** Part of DOE's hydrogen demonstration projects

3. CHALLENGES

Despite its technical promise, nuclear hydrogen faces several deployment challenges:

- **Economic Viability:** Nuclear-derived hydrogen remains more expensive than conventional methods like steam methane reforming. However, policy instruments such as Contracts for Difference (CfDs) - used in the UK to support low-carbon electricity - and production tax credits (e.g., the U.S. Inflation Reduction Act's \$3/kg hydrogen incentive) can significantly improve competitiveness. These mechanisms reduce investor risk and create predictable revenue streams, helping bridge the cost gap.
- **Infrastructure Requirements:** Large-scale deployment demands investment in hydrogen storage, compression, purification, and

distribution systems. Co-location with nuclear facilities can reduce infrastructure costs but requires careful integration.

- **Geographic Mismatch:** Nuclear plants are often remote, while hydrogen demand is concentrated in industrial hubs. This spatial disconnect necessitates strategic siting or investment in transport infrastructure.
- **Competing Demand for Nuclear Electricity:** Diverting nuclear output for hydrogen production may impact grid reliability, especially during peak demand. Flexible load-following strategies and hybrid energy systems can help balance priorities.
- **Regulatory Complexity:** Co-locating hydrogen systems with nuclear facilities introduces new safety and licensing considerations. Clear regulatory frameworks and early engagement with authorities are essential to streamline approvals.

By combining technology innovation with targeted policy support, nuclear hydrogen can become a viable pillar of clean energy strategies.

While deployment challenges are global in nature, specific regional contexts help illustrate their complexity. For example, in Ontario, Canada, the strong reliance on nuclear power for baseload electricity creates a challenge in allocating capacity for hydrogen production without compromising grid reliability. Additionally, the geographic separation between nuclear facilities and hydrogen demand centers - common in many countries - adds logistical and economic hurdles for hydrogen transport. Similar challenges are observed in other regions such as France, Japan, and the United States, where nuclear infrastructure is robust but often distant from industrial hydrogen users. These examples underscore the importance of strategic siting, co-location with hydrogen demand hubs, and flexible operational strategies to balance electricity and hydrogen production.

4. CONCLUSION

Hydrogen production using nuclear energy presents a promising pathway for decarbonizing hard-to-abate sectors and enhancing energy system flexibility. This paper has explored multiple production methods - electrolysis and thermochemical cycles - and evaluated their integration with nuclear technologies.

Alkaline electrolysis is currently the most viable option for near-term deployment due to its commercial maturity, cost-effectiveness, and compatibility with the steady baseload electricity output from existing nuclear power plants. For future applications, High-Temperature Steam Electrolysis (HTSE) offers significantly higher efficiency by leveraging both electricity and thermal energy. While advanced reactors such as HTGRs and MSR can enhance HTSE performance, the process can also be implemented using low- to mid-grade heat from existing Light Water Reactors (LWRs), albeit with reduced efficiency.

Thermochemical water-splitting cycles, such as the Sulfur-Iodine and Calcium-Bromine processes, offer long-term potential due to their ability to use heat alone. However, their high temperature requirements (>800 °C), engineering complexity, and low technology readiness level currently limit their deployment.

Key challenges for nuclear hydrogen deployment include economic competitiveness, infrastructure development, geographic mismatch between nuclear sites and hydrogen

demand, and regulatory complexity. Addressing these barriers will require coordinated efforts in technology development, policy support, and system integration.

Overall, nuclear hydrogen production - when strategically deployed - can play a critical role in achieving deep decarbonization and energy security goals.

Nuclear-powered hydrogen production could reshape energy markets. In Canada alone, with 4 Mtpa hydrogen output and over 5 Mtpa of clean hydrogen projects underway, low-carbon nuclear hydrogen could meet up to 18% of national energy demand by 2050. Globally, the nuclear-hydrogen integration market was valued at USD 1.82 billion in 2024 and is projected to grow to USD 4.18 billion by 2033, suggesting substantial investment and capacity expansion.

Critically, this scale supports key hard-to-electrify sectors: aviation (potentially reducing emissions by up to 90%), shipping, ammonia production, and heavy industry. Large-scale deployment of nuclear hydrogen thus offers a powerful lever for decarbonization, complementing electrification strategies.

Nuclear-powered hydrogen - commonly referred to as pink hydrogen - offers a low-carbon alternative that complements green hydrogen (from renewables) and blue hydrogen (from fossil fuels with carbon capture). While green hydrogen is ideal for regions with abundant renewable resources, and blue hydrogen serves as a transitional solution, pink hydrogen leverages the reliability and scalability of nuclear energy. Its ability to provide consistent baseload power and high-temperature heat makes it particularly suited for industrial applications and long-duration energy storage. As part of a diversified hydrogen strategy, pink hydrogen can play a pivotal role in achieving deep decarbonization, especially in countries with strong nuclear infrastructure.

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Shahram Assadi is a Senior Project Manager based in Toronto, Ontario, Canada with extensive experience leading complex, cross-functional initiatives in the technology and engineering sectors. With a strong background in project delivery, stakeholder engagement, and strategic planning, Shahram has successfully managed high-impact programs across diverse industries. He is known for his structured approach to problem-solving, commitment to quality, and ability to drive innovation through collaboration. Shahram holds a proven track record of delivering results in dynamic environments and is passionate about leveraging technology to create sustainable and scalable solutions.



ACRONYMS

| | |
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| ALK | Alkaline Electrolysis |
| Ca-Br | Calcium-Bromine Cycle |
| DOE | U.S. Department of Energy |
| HTE | High-Temperature Electrolysis |
| HTGR | High-Temperature Gas-Cooled Reactor |
| HTSE | High-Temperature Steam Electrolysis |
| IAEA | International Atomic Energy Agency |
| LCOE | Levelized Cost of Electricity |
| LWR | Light Water Reactor |
| LFR | Lead-cooled Fast Reactors |
| MSR | Molten Salt Reactor |
| OECD | Organisation for Economic Co-operation and Development |
| PEM | Proton Exchange Membrane |
| MSR | Molten Salt Reactors |
| NEA | Nuclear Energy Agency |
| PGMs | Platinum Group Metals |
| SAF | Sustainable Aviation Fuel |
| SMR | Small Modular Reactor |
| SOEC | Solid Oxide Electrolysis Cell |
| S-I | Sulfur-Iodine Cycle |
| SFR | Sodium-cooled Fast Reactors |
| TRL | Technology Readiness Level |
| VHTR | Very High Temperature Reactor |

NOTES:

Efficiencies shown are indicative and represent a mix of current practical values and future potential under optimal conditions. For electrolysis methods, efficiencies are typically based on the ratio of hydrogen energy output (HHV) to electrical input, without accounting for upstream conversion losses from nuclear heat to electricity. For thermochemical cycles, efficiencies are based on total thermal input. As such, values may not be directly comparable across all methods. Thermochemical cycle efficiencies are still under investigation and may vary significantly depending on system design and integration. The efficiency values for Sulfur-Iodine and Calcium-Bromine cycles are based on theoretical estimates and assume ideal integration with high-temperature heat sources. These values are not yet demonstrated at commercial scale.

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