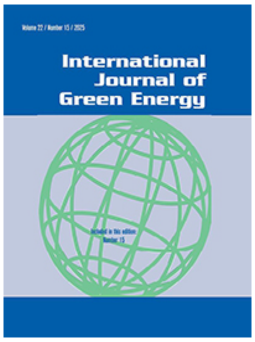

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High-level hazard analysis for pink hydrogen production

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ABSTRACT

Pink hydrogen produced using nuclear-powered electrolysis emerges as a promising zero-emission solution. However, integrating high-temperature processes and nuclear-derived electricity for pink hydrogen production poses inherent safety risks. Hydrogen presents specific challenges due to its unique properties, including high flammability, wide explosion limits, and rapid diffusion. When coupled with nuclear power systems, these challenges are amplified, as the interaction between two inherently high-risk systems introduces new hazards and complexities. Furthermore, pink hydrogen is relatively new to industry and requires comprehensive safety protocols for its safe operation and production. This research conducts a detailed high-level hazard analysis to identify, assess, and control potential risks related to pink hydrogen production. Data and information were gathered through extensive research and team discussions. Various scenarios and consequences were assessed to ensure safe operation and plant performance. Initially, 26 high-risk scenarios were identified. Following implementation of mitigation measures, the number of high-risk scenarios was reduced to 2, demonstrating the effectiveness of the proposed controls. Implementing these recommendations and design modifications will help manage overall plant risk to a tolerable level. By addressing safety concerns proactively, this analysis contributes to the safe development and advancement of pink hydrogen technology for a sustainable future.

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Electrolysis; hazard identification; hazards analysis; nuclear hydrogen; Pink hydrogen; qualitative risk assessment; solid oxide electrolysis cells

Introduction

Hydrogen is a versatile and energy-dense gas with the ability to contain high energy per unit of weight, which is very useful as an energy carrier (Yue et al. 2024). Hydrogen molecules have a high auto-ignition temperature but can easily combust in the presence of ignition sources due to their very low ignition energy, with higher flame velocity and diffusion rate than conventional hydrocarbon gases (Huang et al. 2015). Fires and explosions can occur within a large flammable range (Amer et al. 2024). Therefore, engineering controls are required to ensure its safe operation and handling. Hydrogen is increasingly recognized as a critical enabler of clean energy systems due to its high energy density and potential for zero-carbon emissions that can help reduce Greenhouse Gas (GHG) emissions (Habib et al. 2024).

Despite their rapid diffusion in the air, high-pressure leaks can result in an unconfined jet fire. Vapor cloud explosions (VCE) and flash fires are serious threats that require strategic planning and measures to prevent and mitigate catastrophic events. The low vapor density of hydrogen makes large-scale capture and storage difficult (Hoseyni et al. 2024). As a result, various technologies are introduced to produce or extract hydrogen molecules (Lahrichi et al. 2024). The technologies are classified based on different color codes as per Figure 1: black, pink, turquoise, yellow, gray, blue, green, and white (Kumar and Lim 2022). Each color has a different environmental impact, and specific technologies are introduced to produce low- and zero-carbon hydrogen to achieve the sustainability goals.

Among various production methods, pink hydrogen produces hydrogen through water electrolysis using nuclear power's process heat and electricity (Ajanović et al. 2022). Pink hydrogen is recognized as a pioneering approach to sustainable energy production for enhanced electrolysis processes. Unlike conventional hydrogen production methods, which usually rely on fossil fuels, pink hydrogen production offers the potential for zero GHG emissions, thereby reducing the impacts of climate change (Fernández-Arias et al. 2024).

However, this integration introduces complex safety challenges, including high-temperature operations, radiation risks, and hydrogen-specific hazards such as flammability and material degradation (Hassan et al. 2024). While extensive research has been conducted on the safety aspects of conventional hydrogen production and nuclear plant operations individually, there remains a significant gap in understanding the unique risks posed by their integration. The current literature lacks comprehensive hazard identification studies tailored specifically to pink hydrogen systems, particularly those that examine the interdependencies between nuclear infrastructure and hydrogen production facilities (Al-Douri and Groth 2024).

This study addresses this gap by conducting a structured Hazard Identification (HAZID) analysis focused on pink hydrogen systems. The novelty of this work lies in its integrated approach, assessing hazards not only within the hydrogen plant but also considering cross-system risks, such as hydrogen explosions impacting nuclear reactor safety systems, electrical interference, and radiation leakage scenarios. The

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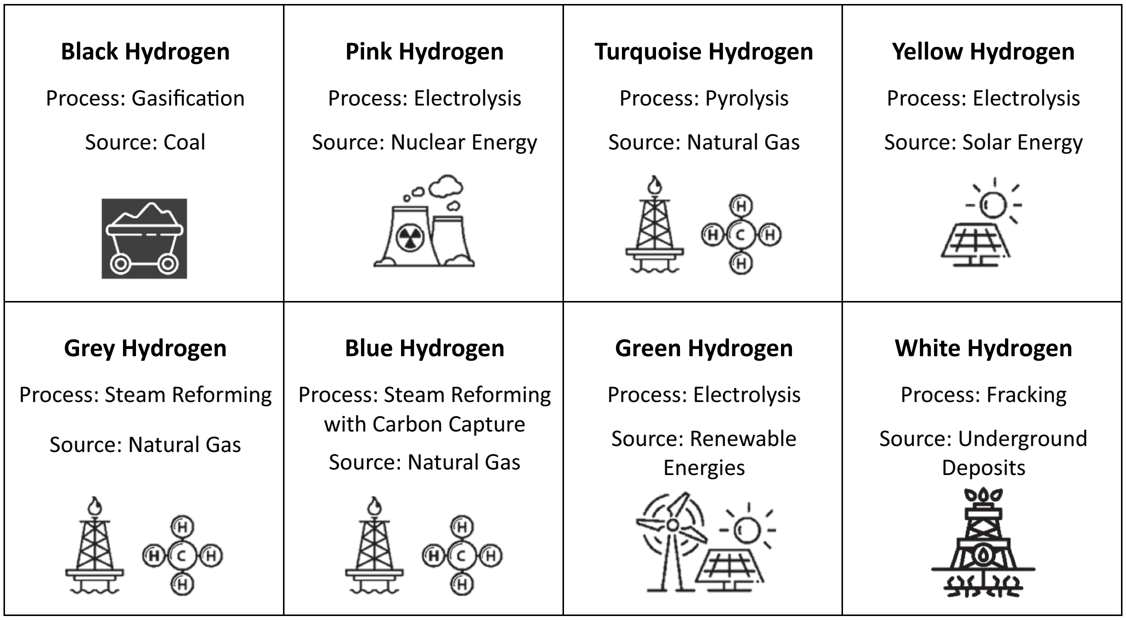

Figure 1. Hydrogen color spectrum (Ajanović et al. 2022).

study further provides design-based recommendations to enhance safety and support the development of reliable, scalable pink hydrogen technologies.

There are four types of electrolysis that are commonly used in industries: Proton Exchange Membrane (PEM), Alkaline Water Electrolyser (AWE), Solid Oxide Electrolysis Cells (SOEC) and Anion Exchange Membrane (AEM) (Sebbahi et al. 2024). Briefly, PEM is very suitable to be used to minimize the corrosion problem; AWE systems are commonly installed in large-scale hydrogen production; SOEC has the ability to operate at high temperatures; and AEM operates on limited current densities for the ion exchange (Şahin 2024).

(i) Proton Exchange Membrane (PEM)

PEM electrolysis cells are built with membrane electrodes, gas diffusion layers, and separator plates [16]. These cells operate at temperatures below 100°C and utilize specially designed electrolytes to support the movement of hydrogen ions across the membrane (Onwuemezie and Gohari Darabkhani 2024). Capable of operating at high current densities exceeding 2 A/cm^2, PEM electrolyzers can improve efficiency and reduced overall costs, while the design supports compact, high-pressure system configurations (Daud and Ramli 2022).

Figure 2 shows how PEM water electrolysis works.

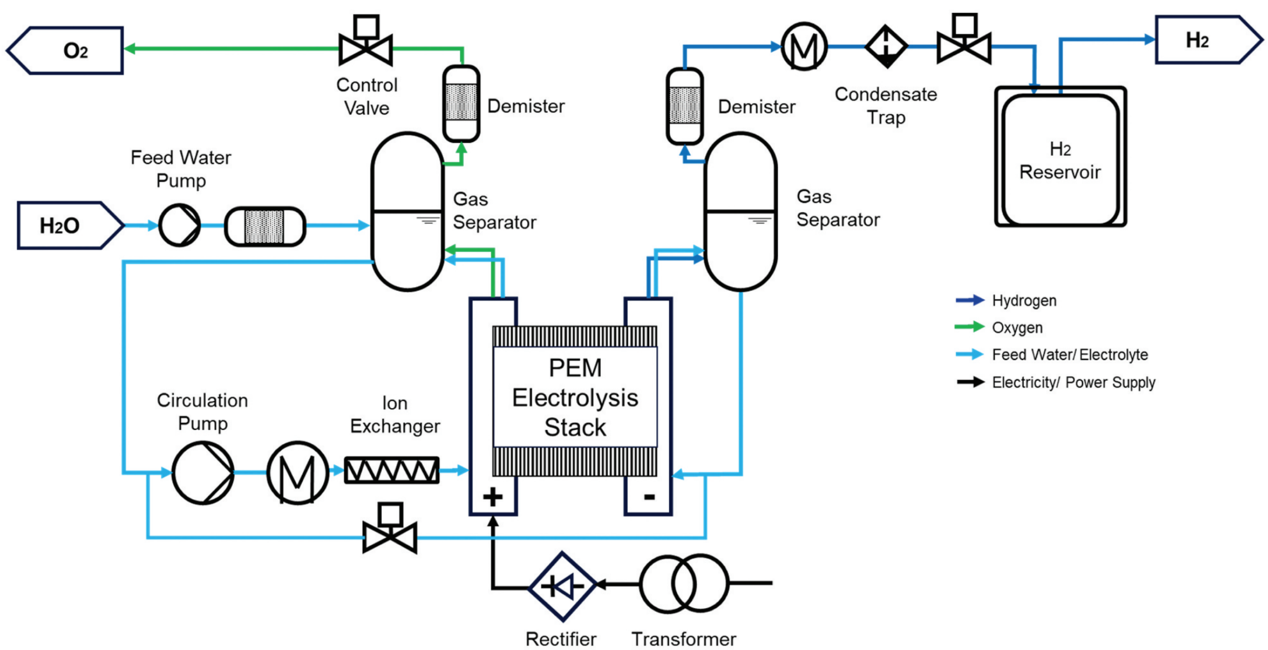

Figure 2. Schematic diagram of a PEM electrolysis system (Daud and Ramli 2022).

Deionized water enters the system through the inlet via a feed water pump and a filter. It then passes through a gas separator, a circulation pump, a series of exchangers, and finally into the electrolysis stack. Further separation takes place in each gas separator to separate the liquid and gas. While the separator eliminates most of the liquid content, a demister is installed at the outlet of each separator to remove fine liquid droplets that remain in the gas stream. Small-entrained mist particles are captured, ensuring cleaner and drier gas. This process will not only improve gas purity but also protects downstream equipment from corrosion, erosion, and fouling (Kolmetz and Dwijayanti 2024). The hydrogen gas is then stored in a H_2 gas reservoir or tank before being distributed to users through a gas header.

In the PEM Electrolysis Stack shown in Figure 3 above, deionized water (H_2O) is broken down into hydrogen (H_2) and oxygen (O_2) using a solid polymer electrolyte membrane. When a direct current (DC) voltage is applied, water at the anode (oxygen electrode) undergoes oxidation, producing oxygen gas, protons (H^+), and electrons (e^-). The protons (H^+) migrate through the membrane to the cathode (hydrogen electrode), where they combine with electrons from the external circuit to form hydrogen gas (H_2) (Daud and Ramli 2022). The acidic nature of the membrane in PEM electrolyzers requires precise hydration control, as membrane drying can result in increased resistance, mechanical degradation, and reduced performance. To maintain adequate hydration, PEM electrolyzers commonly depend on external humidification systems such as bubble humidifiers, spray nozzles, or membrane humidifiers (Qi et al. 2025).

(ii) Alkaline Water Electrolyser (AWE)

Operating at temperatures between 60°C and 80°C, AWE is commonly installed in large-scale hydrogen production and stands out as a prevalent choice due to its lower capital costs (Kawaguchi et al. 2023). AWE systems typically operate under moderate thermal conditions and utilize standard liquid water feed. However, frequent thermal cycling during rapid start-up and shutdown can introduce temperature fluctuations that contribute to material fatigue and corrosion over time AWE uses a molten potassium hydroxide (KOH) solution as the electrolyte, which poses a high risk of internal corrosion. Additionally, AWE typically exhibits lower current densities and a limited partial load range compared to other electrolysis technologies (Zorica et al. 2014).

From Figure 4, raw water feed entering the system via filters and separator, the raw water then injected to the KOH Lye stream to get the correct concentration before introducing to the electrolysis stack. The electrolyte is continuously circulated, either by pumps or through natural convection driven by temperature differences and the buoyancy of gas bubbles. It is separated into two distinct drums, or gas-liquid separators, one for each product gas (O_2 and H_2). The KOH lye streams from both sides return to the electrolyzer, which can result in the mixing of dissolved gases within the electrolyte. To avoid the formation of a flammable mixture, proper control of KOH lye circulation is essential. If not managed correctly, hydrogen can accumulate on the anode side, potentially creating a hazardous condition that may lead to fire or explosion (Buttler and Spliethoff 2018). Similar to PEM, AWE products are subsequently stored in separate tanks before being distributed to end users through dedicated gas headers.

In an alkaline electrolysis stack, two electrodes are submerged in a liquid electrolyte consisting of a 25% to 30% KOH solution, with an ion-permeable diaphragm installed between them, see Figure 5. When a DC voltage is applied, water (H_2O) is broken down into hydrogen (H_2) and hydroxide ions (OH^-) through electrolyte KOH/H_2O. Two molecules of OH^- at the anode will further reduce to Oxygen (O_2), water (H_2O), and electrons (e^-) (Gallandat et al. 2017).

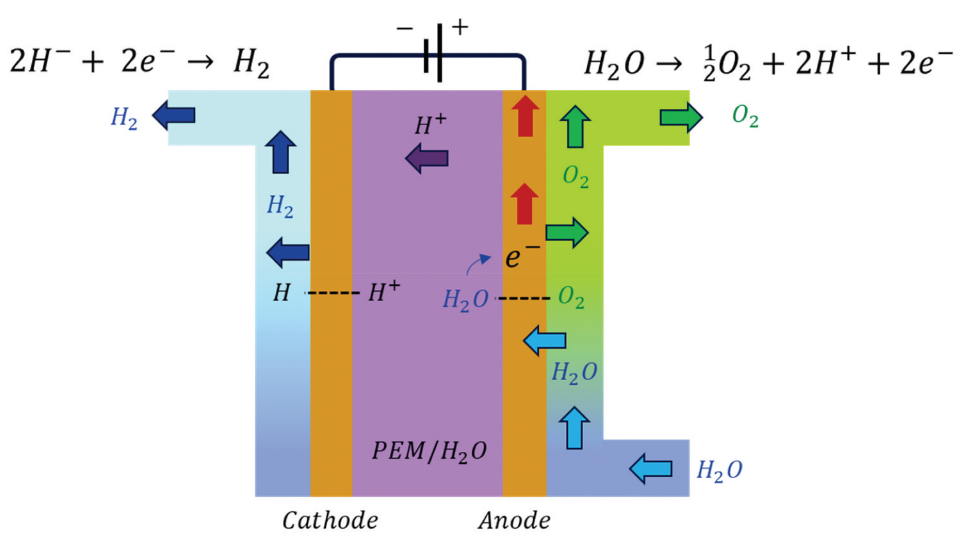

Figure 3. PEM electrolysis stack (Gallandat et al. 2017).

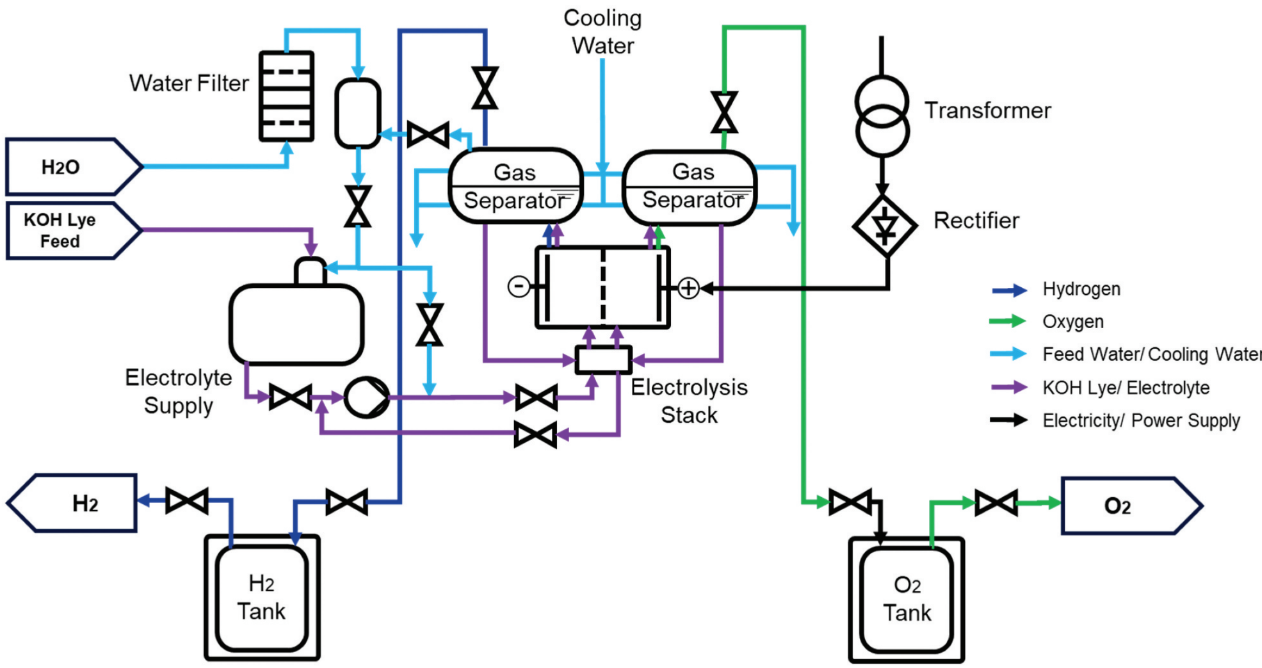

Figure 4. Schematic diagram of an AWE electrolysis system (Daud and Ramli 2022).

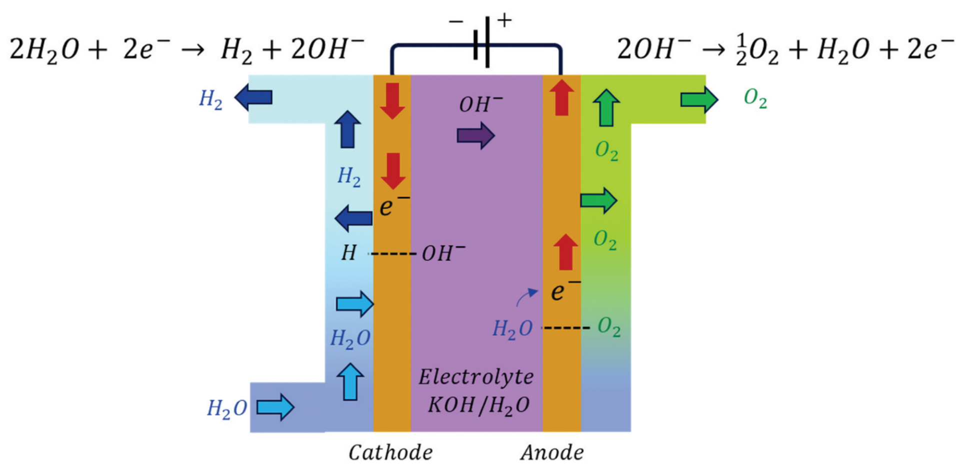

Figure 5. AWE electrolysis stack (Gallandat et al. 2017).

(iii) Solid Oxide Electrolysis Cells (SOEC)

SOEC is an electrochemical device that is designed to directly convert water into hydrogen and oxygen gases (Vostakola et al. 2023). SOEC operates at significantly higher temperatures, typically ranging from 500°C to 1000°C (Onwuemezie and Gohari Darabkhani 2024). SOEC typically made of three distinct forms, the oxygen ion conducting, proton conducting system stacks, and mixed-ion conductor (Lahrichi et al. 2024).

SOEC is said to be the most suitable electrolysis method to be used for nuclear or pink hydrogen production (Revankar 2019). This high-temperature operation offers several benefits that make SOECs particularly suitable for large-scale hydrogen production applications. According to Zhang et al. (2023), SOEC has faster reaction kinetics and improved ion conductivity through the solid oxide electrolyte, thereby enhancing overall electrolysis efficiency. Moreover, the operating temperature range is within the typical nuclear reactor outlet temperatures, 750°C to 950°C (Wilson 2010). Operated with high-temperature steam, making vapor handling is part of the system. While this eliminates the need for additional humidification systems, it places significant demands on material robustness and thermal management. Thermal stress can lead to issues such as sealing failures, material degradation, and long start-up times. As a result, effective thermal design and the use of durable, heat-resistant components are critical to ensuring reliable and safe operation (Li et al. 2022).

Feed water pump deliver the raw water to the recuperator to raise the water temperature before entering the high-temperature pre-heater. Figure 6 illustrates the high-temperature pre-heater is installed at the

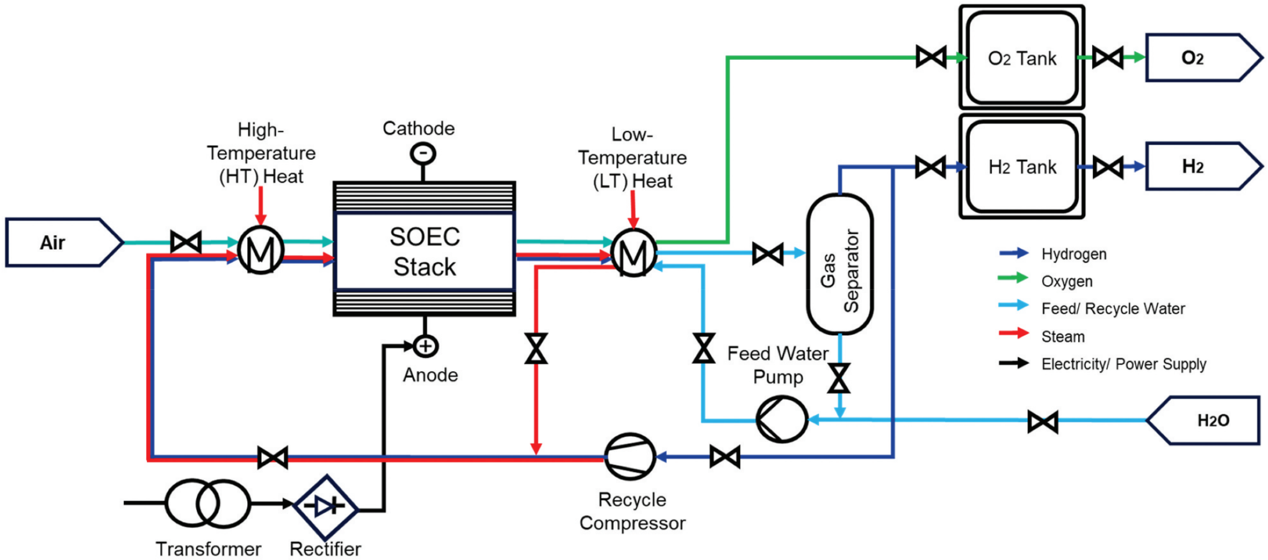

Figure 6. Schematic flow diagram for a high-temperature SOEC (Daud and Ramli 2022).

inlet of the SOEC stack to further raise the temperature of the incoming feed gases, such as air or steam, to near the operating temperature of the SOEC stack (Basso et al. 2024). This preheating reduces the amount of electrical energy required for the electrolysis process by ensuring the gases enter the cell at an optimal temperature. Meanwhile, a recuperator is installed at the outlet of SOEC stack as a heat exchanger that captures waste heat exiting the SOEC and transfers this heat to the incoming feed gases. By recycling this thermal energy, the recuperator minimizes energy losses and lowers the system's overall energy consumption (Todorov et al. 2025).

Figure 7 shows the water molecules at the cathode undergo a reduction reaction where they gain electrons and split into hydrogen gas (H_2) and oxide ions (O^{2-}). The hydrogen gas is released from the cathode surface, while the oxide ions move through the solid oxide electrolyte (ion exchange membrane) toward the anode. Upon reaching the anode side, these oxide ions undergo oxidation, releasing oxygen gas (O_2) and electrons. The oxygen gas is then emitted from the anode surface, and the freed electrons flow back through an external circuit to the cathode, driven by the electric potential difference (Kumar and Lim 2022).

(iv) Anion Exchange Membrane (AEM)

AEM is less common in high-temperature industries due to low operating temperature (Kawaguchi et al. 2023). This technology is offering low hardware costs and long durability, but it has limitations in terms of operating current density and gas purity. AEM combines the advantages of both AWE and PEM (Xu et al. 2022).

AEM producing hydrogen through water electrolysis using an advanced membrane-based electrolyzer

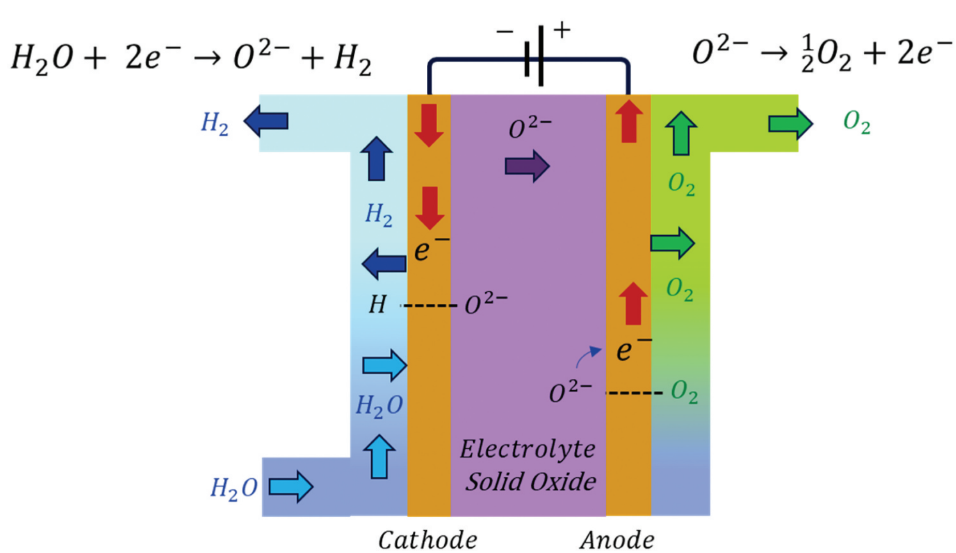

Figure 7. SOEC electrolysis stack (Gallandat et al. 2017).

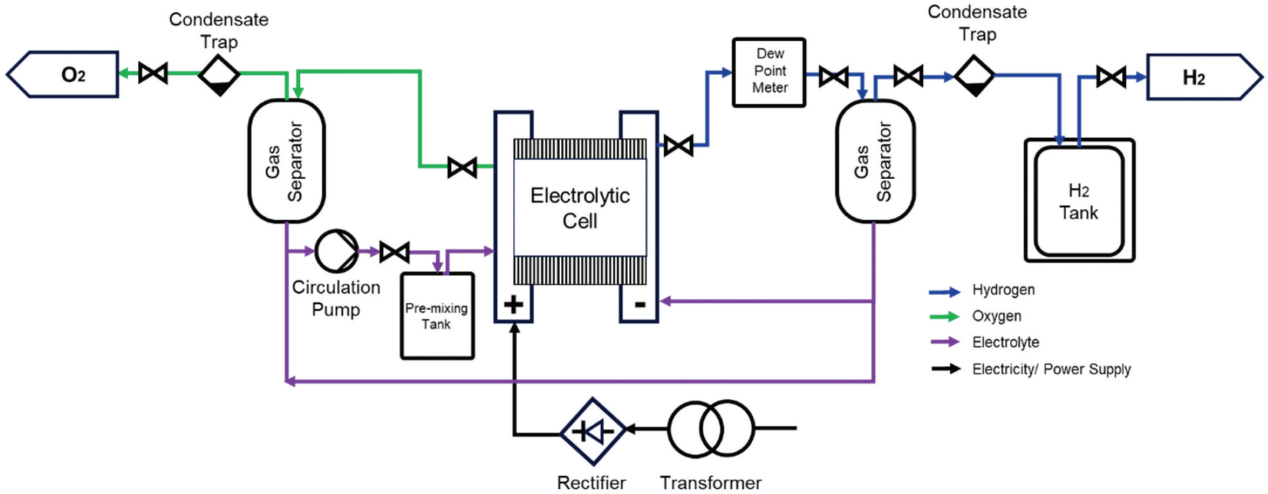

Figure 8. Schematic diagram AEM (Bernat et al. 2024).

(Kawaguchi et al. 2023). The electrolyzer operates using either deionized water or aqueous KOH as the electrolyte, depending on the system design and performance requirements. Figure 8 above shows the liquid electrolyte in AEM system is circulated through both the anode and cathode. Circulating the electrolyte through both electrode compartments helps ensure complete humidification of the AEM and full saturation with hydroxide ions (OH^-) (Pushkareva et al. 2023). AEM performance is highly sensitive to relative humidity (RH). Studies have shown that system efficiency varies with humidity levels; for example, supplying water to the anode and humidified gas to the cathode can deliver good performance, but only when RH is carefully optimized, typically around 80%. At elevated temperatures, membrane stability becomes a concern, and inadequate hydration can exacerbate issues such as gas crossover and reduced ionic conductivity. To maintain consistent performance, it is often necessary to humidify or supply water to both electrodes (Tricker et al. 2023). Figure 9 shows the AEM Electrolysis stack and the reactions.

AEM membranes allow hydroxide ions (OH^-) to migrate from the cathode side toward the anode. This ion transport not only facilitates the necessary reduction and oxidation reactions at each electrode but also ensures the continuous conduction of charge across the cell, maintaining electrical neutrality and enabling stable operation. At the cathode, water molecules undergo electrochemical reduction, producing hydrogen gas and releasing OH^- ions. These hydroxide ions travel through the membrane to the anode, releasing oxygen gas and completing the overall water-splitting process (Bernat et al. 2024).

Following gas generation in the cell, hydrogen and oxygen streams are directed to individual liquid–gas separators to remove entrained water or electrolyte droplets, ensuring gas purity and protecting downstream systems (Bernat et al. 2024). The dried gases are subsequently stored in dedicated tanks under controlled storage conditions.

Comparing all four technologies, each technology has its own unique strengths and limitations. However, SOEC is known to

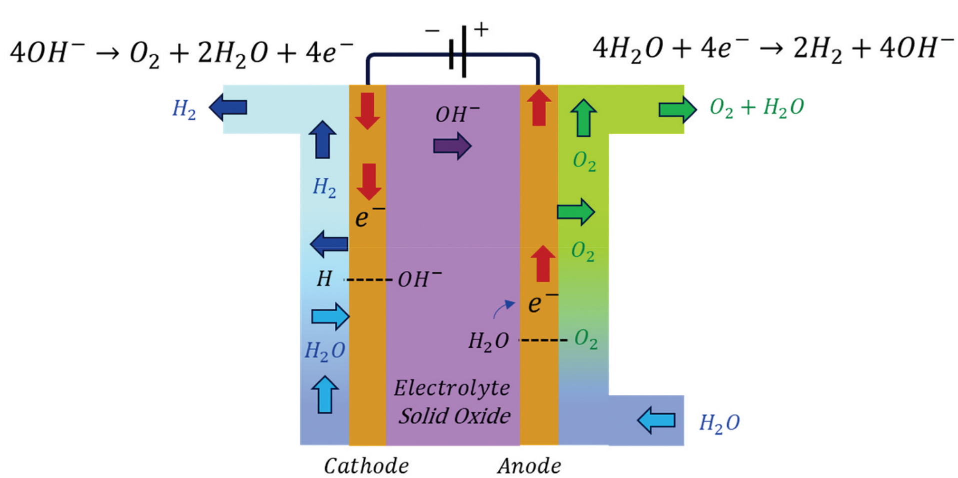

Figure 9. AEM electrolysis stack (Gallandat et al. 2017).

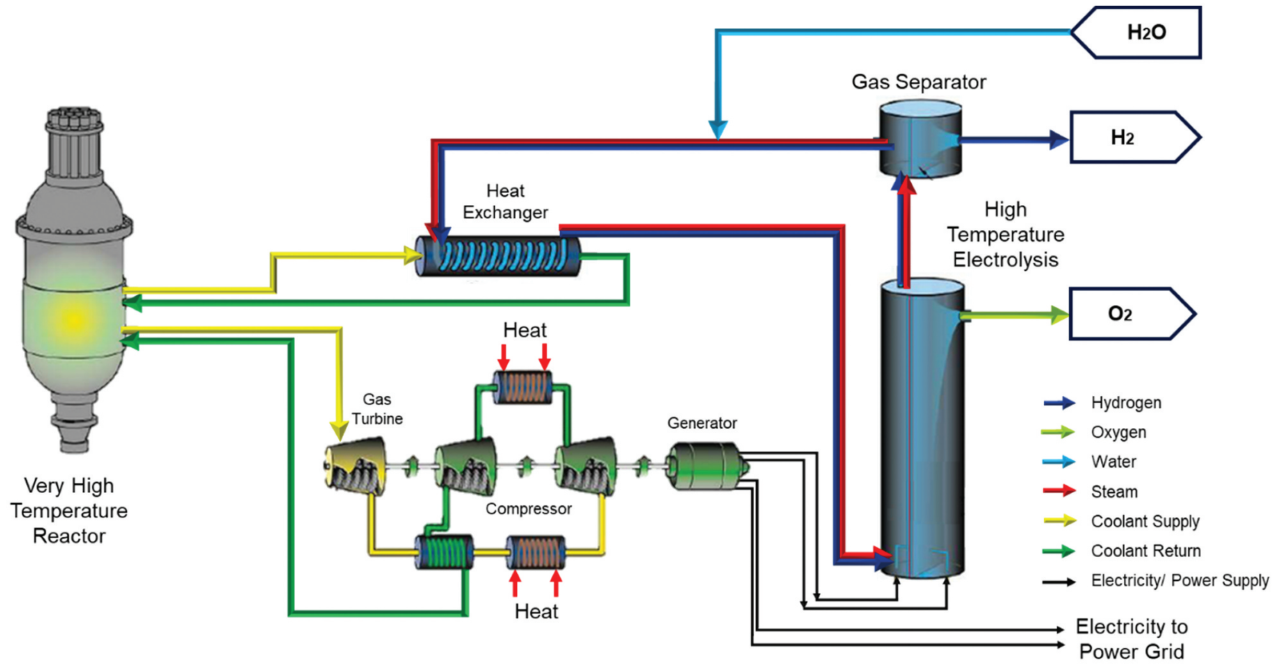

Figure 10. High-temperature electrolysis (HTE) system for hydrogen production (Li et al. 2022).

be capable of operating at high temperatures and can achieve high efficiencies which, making it compatible with the process heat generated by nuclear reactors (U.S. Department of Energy 2020).

The main advantage of high-temperature electrolysis is the improved thermodynamic efficiency. At higher temperatures, the energy required for splitting water molecules into hydrogen and oxygen decreases, leading to improved overall energy efficiency per unit of hydrogen produced (Zhang et al. 2023). Hence, using nuclear reactor process heat for high-temperature electrolysis will be a sustainable energy solution. The heat is repurposed, which aligns with co-generation principles of maximizing resource use while minimizing environmental impact (Jan et al. 2022).

Integrating nuclear process heat into hydrogen production systems requires well-designed heat-transfer mechanisms to ensure both efficiency and safety. As shown in Figure 10, high-temperature nuclear reactors use a primary coolant loop to transfer heat away from the reactor core. Common coolants such as helium, molten salt, liquid sodium, and carbon dioxide are selected for their high thermal conductivity and stability at elevated temperatures. These primary loops can operate between 750°C and 1000°C, making them suitable for hydrogen production processes (Jaszczur et al. 2016).

An intermediate Heat Exchanger (HEx) is used to transfer heat from the reactor's primary loop to a non-radioactive secondary loop, ensuring both thermal integration and physical separation between the nuclear system and hydrogen production processes. This configuration helps prevent radioactive contamination and facilitates modular system design. The secondary loop carries the transferred heat to the hydrogen production plant, where careful insulation and flow-system design are essential to minimize heat losses and maintain high efficiency (Elder and Allen 2009). Once transferred, thermal energy can be applied to hydrogen production technologies, also known as high-temperature electrolysis (HTE). SOEC requires both high-grade steam and electrical power. Therefore, the feed water is preheated into steam using the process heat, significantly reducing the electrical energy required for electrolysis and improving overall efficiency. Integration with the nuclear plant involves both thermal and electrical connections. Heat is delivered via heat exchangers, while electricity can be supplied directly from the reactor's turbine-generator, enabling a cogeneration approach (Li et al. 2022).

However, nuclear hydrogen generation involves several challenges that must be addressed in order to reach its full potential. One of the primary challenges is ensuring the safety of integrating high-temperature processes and hydrogen production (Hassan et al. 2024). Achieving efficient integration requires precise thermal matching between the reactor's heat output and the thermal demands of the hydrogen production system. While nuclear reactors typically operate at a constant output, hydrogen production may experience fluctuations in demand, making it necessary to incorporate thermal storage or other energy management solutions. Furthermore, all system components must be designed using materials capable of withstanding high temperatures, corrosive environments, and significant thermal stress (Fujiwara et al. 2008).

The combination of high temperatures and hydrogen gas exhibits inherent safety risks, especially concerning the flammability of hydrogen and the need to maintain nuclear safety barriers. These risks require rigorous risk assessment, mitigation measures, and safety protocols to avoid accidents and protect personnel, the environment, assets, and surrounding communities (U.S. Department of Energy 2017). Managing nuclear radiation during nuclear power plant upset poses technical, planning, and regulatory challenges. Addressing these effectively is crucial for ensuring the long-term sustainability and acceptance of nuclear hydrogen production as a viable clean energy solution (Anekwe et al. 2025).

The development of hazard identification and risk assessment (HIRA) for pink hydrogen is still in its early stages, as the technology itself is relatively new and part of a growing hydrogen economy (Fernández-Arias et al. 2024). Therefore, significant efforts must be made to adapt and expand safety approaches to meet the unique challenges introduced by the integration of hydrogen production and nuclear energy. The following describes main safety issues in the pink hydrogen industry:

(i) Handling hydrogen: To avoid leaks and reduce risks of ignitions, hydrogen must be handled and stored safely (Ireland et al. 2025).
(ii) Hydrogen embrittlement: Hydrogen can embrittle metals causing structural damage to equipment and infrastructure and posing a safety risk (Ilasko 2024).
(iii) Transport safety: Transporting hydrogen safely over long distances can be difficult due to its low energy density and the need for specific containers or pipes (Calabrese et al. 2024).
(iv) Public awareness: It is important to ensure that the public is aware and trained of the safety risks associated with hydrogen (Guo et al. 2024).

The need for hazard analysis in operating the pink hydrogen production facilities is critical, especially when considering the significant gap in research that specifically addresses the unique challenges that arise from the integration (Muthiah et al. 2024). The integrated technologies pose complex risks. In order to reach its full potential, one of the primary challenges must be addressed which is the safety of integrating high-temperature processes and hydrogen production (Hassan et al. 2024). An explosion in the hydrogen production plant could cause significant damage to infrastructure at the nearby nuclear power plant. Furthermore, the shockwave from a hydrogen explosion may impair the operation of the nuclear facility's safety systems (Hu et al. 2024). High voltage electricity used in pink hydrogen production adds another layer of potential hazards when these facilities are close to one another. The impact of the electrical interference is particularly concerning in a nuclear plant, the disruption could give erroneous readings and lead to malfunctioning controls, increasing the risk of a serious incident. Similarly, equipment in the hydrogen production facility could be damaged by any disruption from the nuclear plant's electrical systems, potentially leading to unsafe operating conditions (IAEA 2011).

Another critical hazard involves the potential release of radiation and its impact on the hydrogen production process. If radiation was to leak from the nuclear plant, radioactive materials could contaminate the hydrogen production facility, posing significant risks to personnel and the environment (Huang et al. 2024). Leaked radiation could disrupt the hydrogen production process, especially if it affects electronic controls, sensors, or materials used in the production process. Addressing these safety concerns effectively is crucial for ensuring the long-term sustainability and acceptance of nuclear-hydrogen production as a viable clean energy solution (Anekwe et al. 2025). Chemical hazards are also a significant concern in pink hydrogen production, encompassing risks associated with exposure to hydrogen gas and any by-products produced during the process. These risks include factors such as flammability, explosiveness, and toxicity (Perelli and Genna 2022). Careful evaluation of environmental hazards is also important throughout all production stages. This includes an assessment of potential impacts on both human health and the environment (Chelvam et al. 2024).

Lowesmith et al. (2014) underlines that Hydrogen production industries mainly use qualitative assessments for risk assessment due to lack of suitable models, limited large-scale data, and the complexity of hydrogen production systems. Asal et al. (2025) note that limited data specific to nuclear-hydrogen production compared to hydrocarbons require conservative assumptions and models for safe design and operation. Recommendations include advanced risk assessment methods and enhanced collaboration between nuclear and hydrogen experts can improve the safety and reliability of nuclear-powered hydrogen production (Gao et al. 2022). Besides, existing research focuses mostly on the individual safety aspects of nuclear or hydrogen facilities, but very few delve into the hazards that arise when these systems are integrated, such as the possibility of hydrogen explosions damaging nuclear infrastructure, radiation contamination, or the dangers of high-voltage electricity. This lack of comprehensive research highlights the importance of detailed hazard analysis in developing effective safety protocols which tailored to nuclear-hydrogen systems and improved data specific to the integration (Al-Douri and Groth 2024).

The common hazards identified are fire and explosion, high temperatures, flow rates, pressures, electrical failures and hydrogen gas pressure (Hadef et al. 2020). The research emphasizes the importance of strict safety protocols and continuous monitoring to minimize risks and ensure safe high-temperature hydrogen operations (Kasai et al. 2016). By improving the understanding and reducing the hydrogen-related risks, we can effectively support the safe integration of hydrogen technologies into global energy infrastructures, thereby facilitating the advancement toward a sustainable future. In this research, to address the mentioned challenges, a HAZID study will be conducted to identify and evaluate the various hazards associated with the pink hydrogen operation and production. Also, assess the adequacy of design measures to help in finding any gaps or opportunities for improvement, allowing for modifications and recommendations to enhance overall hydrogen production safety.

The objectives of this research paper are to identify and assess the various hazards associated with the pink hydrogen operation and production. This includes analyzing potential scenarios that could lead to accidents, as well as understanding their possible consequences. This process involves scrutinizing every aspect of the plant to ensure all potential risks are considered. Additionally, the adequacy and effectiveness of existing mitigation measures are assessed which helps in finding any gaps or opportunities for improvement, allowing for adjustments and recommendations to enhance overall hydrogen production safety. The novelties and new insights in this paper can be highlighted as follows:

(i) Emphasizing the inherent risks: This project underscores the risks associated with a pink hydrogen plant, highlighting its high-risk nature.
(ii) Integrated technologies: The paper not only considers nuclear or hydrogen production plants in the hazard analysis but also extends the analysis to examine the potential consequences across both plants, which reveals an extensive list of hazards.
(iii) Providing concrete recommendations: The study identifies all potential hazards and offers recommendations to ensure the efficient and safe production of zero-carbon hydrogen, protecting both people and the environment while advancing sustainability goals.

The research paper adds to the growing knowledge on sustainable energy solutions and aims to inspire further research and development of pink hydrogen technologies (Hassan et al. 2024).

The remainder of this paper is organized as follows: Methodology discusses the research methodology to identify and assess the specific hazards of pink hydrogen. Results and discussion section provides the results and the discussion of the hazard analysis, and lastly Conclusion, which is a summary of key insights.

Methodology

Hazard identification (HAZID)

HAZID study will use a list of guide words to evaluate all possible hazards, including the sources, consequences, preventive measures, and mitigation measures. This is considered a preliminary assessment compared to other hazard analysis tools such as HAZOP, Bowtie Study, and LOPA (VISTA Oil & Gas 2019).

Preparation

Sufficient information is required prior to the assessment.

1) Scope of Study

The scope of study should be clearly mentioned in the assessment worksheet, such as facility and modes of operations to be covered.

2) Information Required

Information that needs to be prepared as below:

(i) HAZID study plan
(ii) Process descriptions
(iii) Technical drawings
(iv) Safety systems list
(v) Other plant data

These documents will be the main references to facilitate the HAZID study. A list of assumptions needs to be prepared to ensure a controllable and manageable discussion.

3) HAZID Study Guide Words

Table 1 shows the typical hazards list used for HAZID assessment.

Process workflow

Figure 11 is the HAZID process flow used for the assessment.

STEP 1: Define the scope and objectives of the study

The scope and objectives of the study need to be clearly defined to ensure a comprehensive assessment and the smoothness of the process. This step will also ensure the unit or area is manageable in terms of the size of the analysis, making the HAZID process more structured and focused.

STEP 2: Describe the process and plant

Describing the process and plant thoroughly by outlining the entire process or plant layout, including equipment, systems, operations, and interactions, will ensure a full understanding of how different elements function together and how they might interact to create potential hazards. It serves as the foundation for the subsequent hazard identification process by providing clarity on the scope and boundaries of the assessment. This detailed description is essential because it enables the HAZID team members to accurately pinpoint where and how hazards may arise, allowing for proactive mitigation strategies to be developed and implemented effectively.

STEP 3: Identify hazards

Relevant hazards from the agreed list should be identified and applied. The intent of the guide word shall be explained to ensure the same understanding across the discussion team.

STEP 4: Identify possible causes

All the possible causes will be listed prior to the assessment, and the causes need to be credible and specific to the study scope.

STEP 5: Assess all credible consequences

Assuming there are no safeguards or preventive measures in place, the worst credible consequences of each cause shall be assessed and recorded. Consequence shall consider the impact on People, Asset, Environment, Reputation and Social.

STEP 6: Identify the existing measures and perform risk rating

List all the existing safeguards for preventing the effects of the hazards. Inherently Safer Design (ISD) is the best safeguard to be considered, especially during the early phase of the modification or project. Safeguards can be hardware as well as administrative controls.

Existing risk rating will be determined at this stage to measure the level of risk without considering any recommendations implemented in the system.

STEP 7: Propose new recommendations and perform risk rating

Recommendations will be proposed when the existing safeguards are not adequate to protect the unit or area under study. The recommendations may be in the form of preventive or mitigative measures. The aim of the recommendations is to reduce the risk to ALARP level.

Mitigated risk ranking will be performed to measure the reduced risk level by considering all the recommendations implemented as per the proposal.

Note: Once all factors were considered and analyzed, continue assessing other hazards from the agreed list by repeating STEP 3 through STEP 7.

Application of risk rating

The risk rating for a hazard is determined by considering and combining the severity of the consequence and the likelihood

Table 1. List of hazards (Mannan 2012; Arendt et al. 2007).

Process Hazards	
Overpressure	Process upsets, offsite sources, process blockage, thermal expansion, connection of process to utility systems, chemical reaction.
Temperature	High – fire, hot surfaces, chemical reaction, ambient temperature, Low – Blowdown, loss of coolant, loss of flow, liquid flashing.
Flow	Low or no flow occurs, High flow occurs/reverse flow occurs.
Abnormal operations	Purging, Flushing, Emergency Shutdown, Start-up.
Emergency operations	An internal fire occurs, an internal explosion occurs, fire-fighting response time, combination failures, emergency system inoperative.
Toxic liquids and gases	Contamination, chemical reactions, corrosion and degradation.
Runaway reaction	Cross-over of oxygen into hydrogen and vice versa. Accumulation of explosive hydrogen/oxygen mixtures or in the storage.
Nuclear radiation	Radiation exposure from nuclear plants.
Leakage	Hydrogen leakage from the stack. Break of membrane of bipolar plates. Seal wear, corroded bolts, ductile failure bolts, vibration on pump/agitator.
Mechanical Hazards	
Equipment Layout	Confinement, escalation following release of explosive or flammable fluid, module layout/proximity, orientation of equipment, predominant wind direction.
Equipment and Instrument malfunction/failures	Level gauge failure, level control failure, reverse flow, coupling failure, control system fault, passing valve, fracture of a pressurized pipe, compartment, vessel failure.
Mechanical moving parts	Compressors, pumps.
Equipment deterioration	Material degradation due to excessive thermal stresses.
Corrosion/erosion	Acidic/caustic electrolyte and electrochemistry, stress corrosion cracking, pitting, external corrosion, lining failure.
Electrical Hazards	
High voltage	Electrical short circuits or discharges.
Electrostatic	Electrolysis process, hydrogen handling, storage, dispensing operations.
Electromagnetic radiation	Infra-red, ultra-violet, laser, radar, and radio frequencies.
Fire and Explosion Hazards	
Stored Flammables	Improper or defect storage, storage design.
Sources of Ignition	Electricity, flares, sparks, hot surfaces, static generation, friction, open flames.
Fire Protection and Response	Active/passive protection, fire/gas detection, blowdown/relief system philosophy, firefighting facilities.
Human Factors	
Human Errors	Action: Not enough time to respond, too soon/too late, wrong sequence, valve left open, isolation error during maintenance, instrument repair error, live equipment opened in error, wrong action, incorrect chemical used, poor assembly, wrong fabrication material. Information: Too much/too little, incorrect/incomplete.
Sampling Errors	Sample not taken, sample not analyzed, test results are delayed, test results are incorrect, sample is thermally unstable, sample is pressure sensitive.
Utility Systems	
Firewater Systems	Plant location, plant layout, pipeline routing.
Fuel Gas	Nearby plants and facilities, residential areas.
Power Supply	Equipment malfunctions, short circuits, voltage fluctuation, external factors, supply chain disruptions.
Steam	Heat sources supply failure, steam distribution system failures.
Natural and Environmental Hazards	
Climate Extremes	Temperature, wind, dust, flooding.
Pollutions	Chemical handling and spills. air emissions, hydrogen storage and handling.
Earthquakes	Tectonic activity, human-induced seismicity.
Erosion	Soil erosion, water erosion.
Waste Management	Improper solid waste management, hazardous waste handling, emission control, recovery and recycling.
Health Hazards	
Physical	Noise, radiation, ergonomics.
Biological hazards	Biological growth in water systems, presence of insects, such as mosquitoes or flies, near plant facilities, biological waste generated during plant operations.
Working Hazards	Working at heights, hazardous equipment, hazardous surfaces, electricity, etc.
Plant/Facilities Siting	
Geographical Infrastructure	Plant location, plant layout, pipeline routing.
Proximity to Population	Nearby plants and facilities, residential areas.

of its occurrence. Table 2 shows the 5 × 5risk matrix to be used to perform the risk ranking.

There are three levels of risk in the risk matrix: Low, Medium, and High. Based on Mannan (2012), each risk level is explained as below:

(1) High – High risk is not acceptable. Further analysis should be performed, and redesign or modification should be introduced to reduce the risk.
(2) Medium – Risk is acceptable, but redesign or modification should be considered if reasonably practical, and further analysis should be performed to give a better estimate of the risk.
(3) Low – The risk is low, and no further risk reduction measures or efforts are required.

HAZID study output

1) Recording

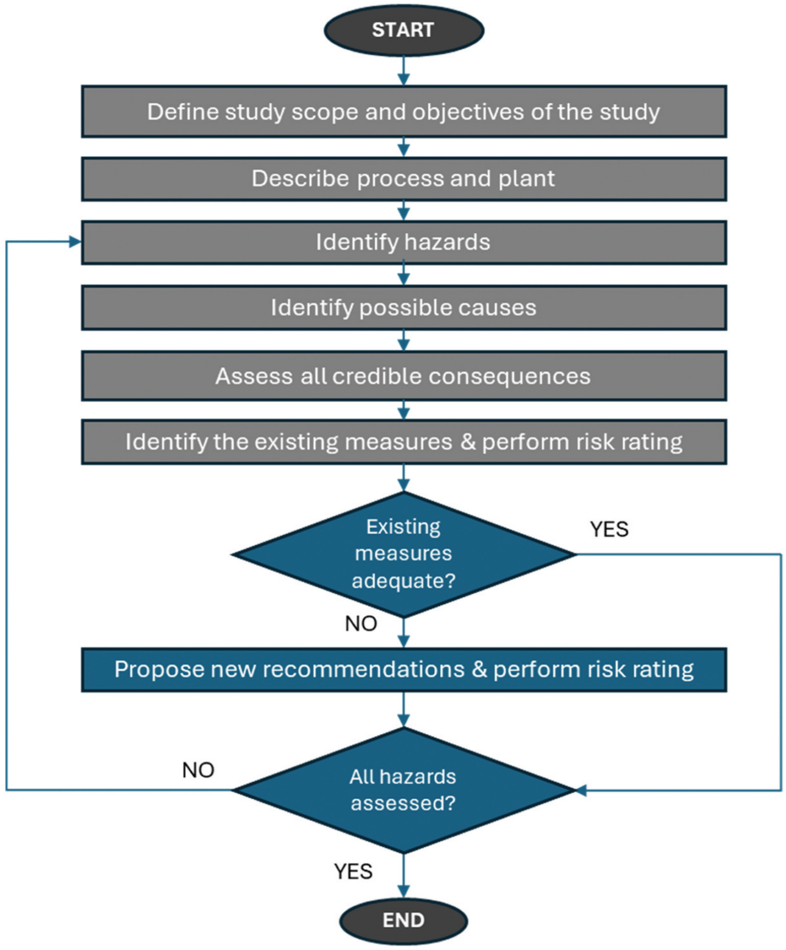

Figure 11. HAZID study process workflow (Mannan 2012).

The HAZID study results will be recorded in the HAZID study worksheet; an example of this worksheet can be found in Table 3.

2) Reporting and Other Documents

The HAZID report is prepared and reviewed prior to its formal and timely issuance. The reports also include the list of recommendations or actions. These risk-ranked activities are then used as the foundation for developing a complete management strategy.

Results and discussion

Hazards list

The list of hazards in Table 1 was analyzed and selected based on the potential scenarios within the scope of the study as per appendix A.1. The summary of main hazards can be found in Table 4, there are 29 hazards identified.

HAZID results and discussion

The analysis identified a total of 52 potential risk scenarios, which were carefully assessed for their likelihood and impact. The details of these scenarios are shown in the appendix A.2 of hazards analysis. Analysis was conducted following sHAZID workflow in Figure 11 for all the hazards identified in Table 5. Due to space limitations, we chose one of them to further explain. The analysis on "Overpressure" hazard with the ID H01.1.1 was conducted:

1) Hazard Identification

2) Possible Scenario, Causes, and Consequences

The scenario involves the overpressure of the feed water system during normal operation, potentially caused by the blockage of reject brine piping due to impurities or resin accumulation. Consequently, this could lead to piping or vessel leaks, resulting in a loss of containment (LOC) of demineralized water, which may cause major injuries, local asset damage, and significant environmental impact.

3) Existing Measures

The list of existing measures or safeguards established:

(i) Routine inspection and preventive maintenance.
(ii) Resin trap to capture the escaped resin at the outlet of the anion and cation exchanger vessels.
(iii) Sight glass at the ion exchange vessels to monitor resin level.

4) Risk Rating

Table 2. HAZID risk matrix (Jharap et al. 2020).

Consequence						Increasing Probability				
Severity Rating	People	Environment	Assets	Reputation	Social	A 10^{-5} to 10^{-4} occurrence/year Rare occurrence Never heard of in the Global industry	B 10^{-4} to 10^{-3} occurrence/year Unlikely occurrence Heard of in the Global industry	C 10^{-3} to 10^{-1} occurrence/year Credible occurrence Incident has occurred	D 10^{-1} to 1 occurrence/year Probable occurrence Happens several times per year	E >1 occurrence/year Likely occurrence Happens several times per year
1	No/negligible health effect/injury	No effect	No damage	No impact	No impact					
2	Minor/Slight health effect/injury	Slight effect	Slight damage	Slight impact	Local impact	Manage for continuous improvement				
3	Major health effect/injury	Localized effect	Localized damage	Considerable impact	Regional impact			Incorporate risk reductive measures		
4	Permanent disability/up to 3 fatalities	Major effect	Major damage	National impact	National impact					Intolerable
5	More than 3 fatalities	Massive effect	Extensive damage	Internation impact	International impact					

Table 3. HAZID worksheet example.

Area:
Drawing Number:
Meeting Dates:

No.	Ref. ID	Hazards	Scenario/Accidental Events (what, where, when)	Causes	Description of Consequences/Major Effects	Existing Safeguards (Corrective/Preventive Measures)	Existing Risk		Recommendations	Mitigated Risk		Remarks
							Probability	Severity		Probability	Severity	

Table 4. Summary table of the main hazards.

Hazards	Remarks
Process Hazards	
Overpressure	Overpressure can occur due to equipment malfunction, process upsets, or pressure control system failures.
Temperature	Hydrogen production processes, especially those involving electrolysis or chemical reactions are sensitive to the temperature changes.
Flow	Accurate flow control is vital in hydrogen production to ensure the correct amount of feedstock for efficient production.
Abnormal operations	Unplanned deviations from normal operational conditions, such as equipment malfunctions, operator errors, or unexpected environmental changes, can pose significant risks in hydrogen production.
Runaway reaction	Maintaining precise control over reaction conditions is critical. Failure could lead to excessive heat, pressure, or even hazardous conditions.
Nuclear radiation	Potential radiation leaks or exposure.
Leakage	Hydrogen is a highly flammable and low-density gas that can easily leak through small openings or faults in equipment. Leakage can cause fires or explosions.
Mechanical Hazards	
Equipment Layout	Poor equipment layout can lead to accidents.
Equipment and Instrument malfunction/failures	Malfunctions or failures can lead to process disruptions, safety hazards, or even catastrophic events.
Mechanical moving parts	Many components in hydrogen production systems involve moving parts, such as pumps, compressors, and valves.
Equipment deterioration	Over time, all equipment in pink hydrogen facilities will experience deterioration due to operational stresses, ageing, and environmental conditions.
Corrosion/erosion	Hydrogen production processes can expose equipment to corrosive environments, especially if moisture or other reactive substances are present.
Electrical Hazards	
High voltage	Electrolysis, which requires the use of high-voltage electrical systems to separate hydrogen and oxygen from water.
Electrostatic	Electrostatic discharge is hazardous because hydrogen is highly flammable.
Electromagnetic radiation	Electromagnetic radiation may be emitted from various equipment used in hydrogen production.
Fire and Explosion Hazards	
Stored Flammables	Hydrogen is highly flammable and requires careful management to prevent accidents.
Sources of Ignition	Source of ignition can pose a significant risk.
Human Factors	
Human Errors	Human errors can occur in various aspects of pink hydrogen production, including operation, maintenance, and safety procedures.
Sampling Errors	Accurate sampling is critical to ensure that the quality and safety of the hydrogen being produced meet required standards.
Utility Systems	
Power Supply	Pink hydrogen production often involves processes that require a reliable and stable power supply.
Steam	Consistent steam supply is required to ensure continuous operation of the pink hydrogen plant.
Natural and Environmental Hazards	
Climate Extremes	Extreme weather conditions can impact the operation and safety of hydrogen production facilities.
Pollutions	Air, water, or soil pollution can lead to contamination of feedstocks, impacting the quality of the hydrogen produced.
Earthquakes	Earthquakes can pose significant risks to the structural integrity of hydrogen production facilities.
Waste Management	The production of pink hydrogen, generates various types of waste, such as by-products from electrolysis or materials used in production processes.
Health Hazards	
Physical	Risks that arise from the physical environment or equipment in the production facility.
Biological	Living organisms that could impact health e.g., microbial contamination.
Working	Working hazards including the working environment and procedures e.g., safe system of work (SSOW).
Plant/Facilities Siting	
Proximity to Population	The close location of a hydrogen facility to residential or commercial areas increases the risk of incidents affecting nearby communities.

Table 5. Overpressure.

Ref. ID	Process Hazards		Remarks
H01.1.1	Overpressure	Process upsets, offsite sources, process blockage, thermal expansion, connection of process to utility systems, chemical reaction.	For example, process upsets caused by abrupt changes in operating conditions or process blockages can result in pressure buildup as the flow of gases or liquids is restricted, leading to increased upstream pressure. These factors make overpressure a significant and foreseeable hazard in pink hydrogen production.

The risk was assessed considering the likelihood and severity of the worst-case scenario. Blockage of the reject brine piping is a possible scenario due to the potential of impurities or resin accumulation in the reject brine pipeline. This blockage could happen approximately once every ten years of vessel operation. The impact would likely result in localized damage to the vessel or equipment, leading to demineralized water leakage within the area. Therefore, the risk rating is C3, which indicates a medium risk.

5) Evaluate the Adequacy of Existing Measures and Proposed Recommendations

Since the risk rating is medium, the system will require to incorporate the risk reduction measure(s). New recommendation was proposed to reduce the risk:

i. Install pre-filters at the inlet of the feedwater line to capture impurities before entering the demineralized water system.

6) Risk Level Reassessment

The risk level has been reassessed to incorporate the new recommendation. The likelihood of the scenario has been reduced from "credible" to "unlikely" due to the installation of a new pre-filter on the feedwater inlet line. Hence, the risk rating has been lowered to B3, indicating a low risk.

The pie chart in Figure 12 shows the risk levels of operating and producing pink hydrogen with existing measures in place.

From the existing risk levels, 26 scenarios were classified as high risk, indicating a significant potential for severe consequences or catastrophic outcomes if not addressed, even with the existing safeguards in place. Twenty-five medium-risk scenarios, where threats exist but the risks are mitigated by existing safeguards. These scenarios may still pose a threat, but with less severe consequences compared to the high-risk scenarios. Finally, there is only 1 scenario was identified as low risk due to its low likelihood of occurrence and the potential impact, suggesting that current controls are adequate to prevent any significant harm. This categorization provides a clear prioritization framework, guiding the focus of mitigation efforts toward the most critical areas to improve overall plant safety.

Following a detailed reassessment of existing safety measures and risk levels, a risk reduction process was implemented. This involved proposing recommendations to mitigate the identified risks and reduce the risk to a tolerable level. The effectiveness of these measures is reflected in the mitigated risk levels, as illustrated in the pie chart shown in Figure 13 below.

With the mitigation measures in place, 2 scenarios remain in the high-risk category, 29 scenarios have shifted to medium risk, and 21 scenarios have been reclassified as low risk.

The significant reduction from 26 to just 2 high-risk scenarios demonstrates the effectiveness of the mitigation measures in addressing the most severe hazards associated with pink hydrogen production. This can be attributed to the improvements in safety protocols, design modifications, and the implementation of additional safeguards, which most likely targeted the primary contributors to high-risk scenarios. The increase in medium-risk scenarios suggests that, while high-risk scenarios were successfully downgraded, many of them are now classified as medium risk. This is a common result in risk reduction efforts, where the risk level is reduced but not eliminated, resulting in a reclassification to a lower but still significant risk category. The major increase in low-risk scenarios, indicates that many scenarios were successfully mitigated, reducing their potential impact and likelihood to minimal levels.

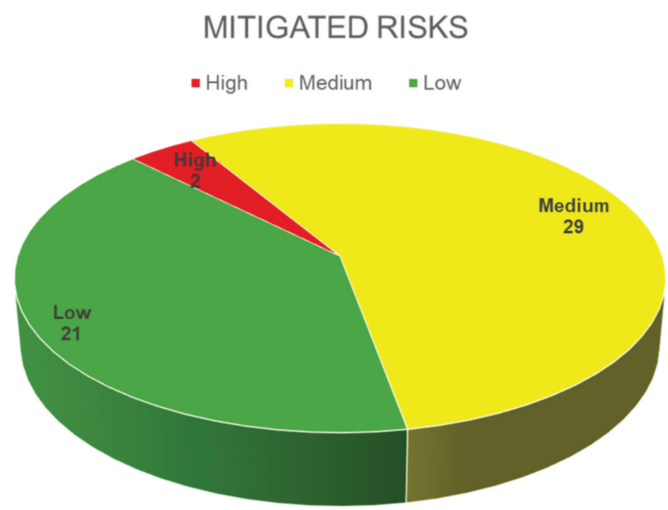

Figure 13. Mitigated risk levels.

While the drastic reduction in high-risk scenarios, the persistence of 2 high-risk scenarios highlights that some hazards remain challenging to fully mitigate. These scenarios may include risks that are inherent to the pink hydrogen production process, which require additional risk management efforts to prevent escalation. Furthermore, the risk profile has shifted, with more scenarios now classified as medium risk. The medium-risk category is now the largest, implying that these scenarios need continuous monitoring to prevent them from escalating back to high-risk levels.

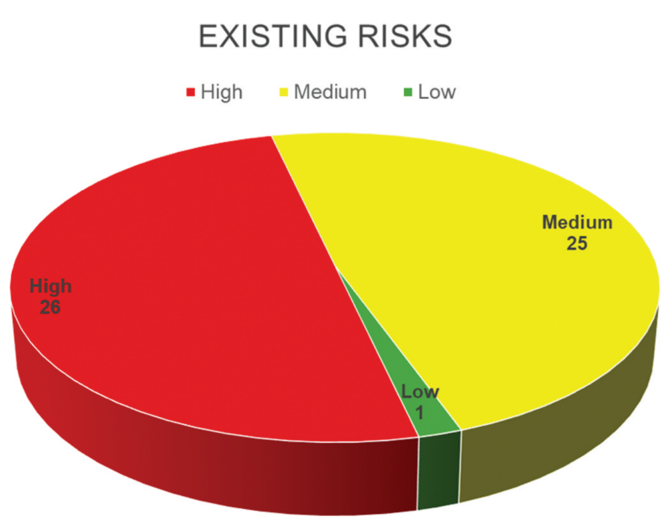

Figure 12. Existing risk levels.

Risk levels

All scenarios with distinct risk levels were analyzed and grouped to provide a clearer understanding of the potential hazards. Referring to Tables 6 and 7, this segregation allows for a more targeted approach in addressing the most critical risks first, while also ensuring that all potential hazards are appropriately managed according to their respective levels of threat. This categorization enables more effective prioritization of mitigation efforts and resource allocation.

1. Existing Risks
2. Mitigated Risks

The bar chart presented in Figure 14 below illustrates the comparison between existing and mitigated risk levels across various risk categories. The blue bars depict the number of scenarios under the existing risks, while the purple bars represent the mitigated risks after

Table 6. Existing scenarios.

Risk Level	Number of Scenarios
High (D5)	8
High (D4)	10
High (C5)	8
Medium (C4)	8
Medium (D3)	1
Medium (C3)	16
Low (C2)	1

Table 7. Mitigated scenarios.

Risk Level	Number of Scenarios
High (C5)	2
Medium (C4)	12
Medium (B5)	12
Medium (B4)	5
Low (B3)	12
Low (A4)	3
Low (B2)	1
Low (A3)	5

implementing the proposed safety measures. This visual comparison highlights the effectiveness of the mitigation strategies in significantly reducing the number of high-risk scenarios, shifting many into the medium and low-risk categories.

Proposed action items

A total of 57 actions were proposed, these are summarized in Table 8. Each action item needs to be implemented to reduce the risk level of the pink hydrogen plant.

The identified primary hazards and key recommendations are summarized in Table 9.

ALARP (As Low as Reasonably Practicable) demonstration

The sub-system HAZID Analysis shown in Tables 10 and 11 provides a more detailed assessment of potential hazards. Both examples allow for a deeper understanding of specific equipment vulnerabilities, operational risks, and targeted mitigation measures.

In particular, the sub-system analysis highlights how risks evolve from the pre-HAZID condition to the post-HAZID condition once mitigation practices are implemented. For example, the SOEC electrolysis, the pre-HAZID analysis identified risks such as high temperature at the electrolysis cell. The mitigation measures introduced included the installation of a temperature controller on the returned electrolyte flow and the incorporation of a high-temperature trip function at the electrolyzer module. The implementation of these measures demonstrates how such risks are controlled. The post-HAZID results show a measurable reduction in both likelihood and consequence ratings, translating to lower overall risk levels.

This explicit pre- and post-HAZID comparison provides evidence of how targeted design features and operational safeguards improve the safety integrity of the subsystem. It also highlights the importance of conducting HAZID at the sub-system level, as this level of detail enables the identification of equipment-specific hazards and the evaluation of practical, implementable mitigation measures.

Considering the high probability and severity of these hazards, the analysis emphasizes the need to prioritize these risks. By addressing these major threats effectively, the overall risk can be significantly reduced to a tolerable

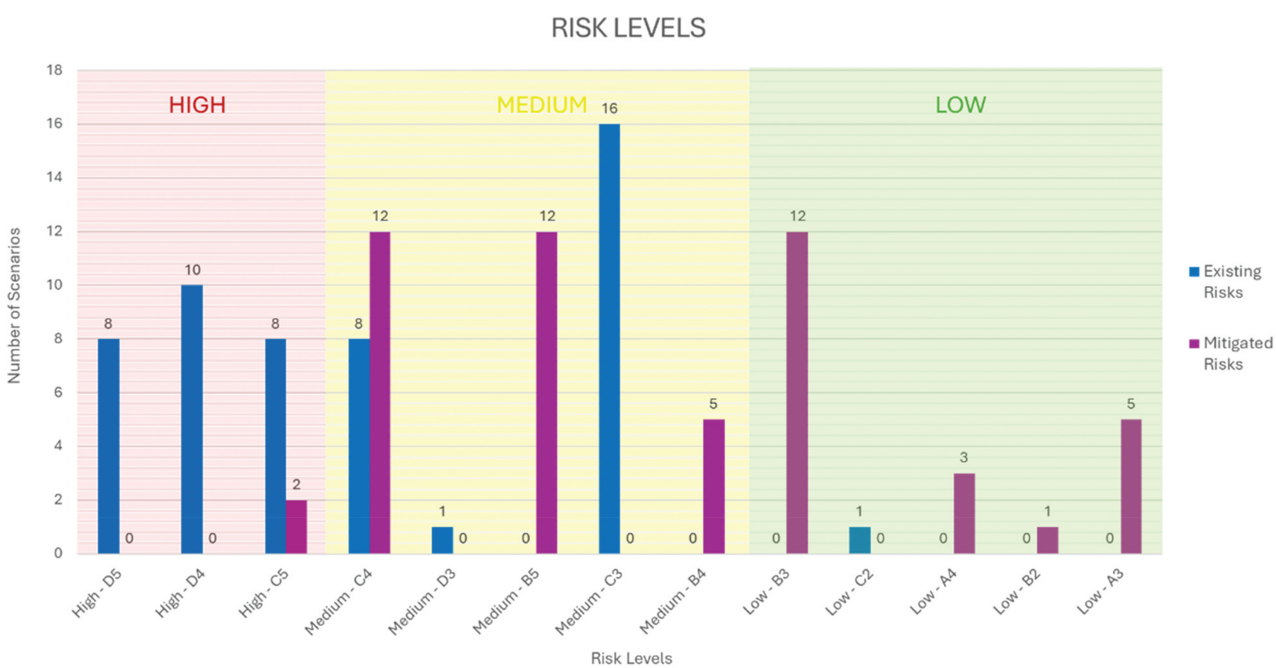

Figure 14. Segregated risks.

Table 8. Action items raised.

No.	Reference ID	Action Item	Risk Level/ Priority
1.	H01.2.1 (1) H09.2.1 (2) H14.2.1 (2) H17.2.1 (2)	Install a high-pressure trip function that will automatically close and isolate the inlet valves and cut off the power to the hydrogen electrolysis unit in the event of high pressure.	High
2.	H01.2.1 (2)	Install Pressure Relief Valves (PRVs) at cell modules, and hydrogen/oxygen outlet lines.	High
3.	H02.1.1 (3) H04.1.2 (1) H07.4.1 (2) H20.4.1 (1) H24.4.1 (2)	Establish communication method/procedure with the nuclear power plant on the plant status and emergencies.	High
4.	H03.2.1 (2) H06.2.1 (1) H08.2.1 (2)	Install an online hydrogen and oxygen analyzer at the outlet of the electrolysis module.	High
5.	H06.2.1 (2)	Perform product sampling to determine the quality of liquified hydrogen gas.	High
6.	H09.2.1 (1) H14.2.1 (1) H17.2.1 (1)	Install a high voltage trip function at the outlet of the rectifier.	High
7.	H14.2.1 (3) H17.2.1 (3)	Improve the preventive maintenance plan by increasing the frequency of high voltage equipment condition and status.	High
8.	H22.4.1 (2) H24.4.1 (1)	Establish communication with the local meteorological department for weather forecasts and updates.	High
9.	H30.4.1 (2)	Establish direct communication with the local authorities and the public on the hazards of the operating plant.	High
10.	H30.4.1 (3)	Provide community awareness training or briefings.	High
11.	H01.1.4 (1)	Install a high-pressure trip function at the pump discharge to trip the pump motor.	High
12.	H01.2.2 (2) H28.1.1 (1)	Establish routine sampling of electrolytes to analyze the quality of demineralized water supply.	High
13.	H01.3.2 (1)	Install a high-pressure trip function at the compressor outlet to shut down the unit and close inlet control valves.	High
14.	H08.2.1 (1)	Install a low-pressure trip function to shut down the hydrogen electrolysis plant, especially the electrolysis cell module.	High
15.	H09.3.1 (1)	Provide proper earthing for the storage vessel, connecting the vessel to the ground.	High
16.	H26.4.1 (1)	Build noise barriers around the large and high-vibration equipment area.	High
17.	H26.4.1 (2)	Use noise reduction technology for the large and high-vibration equipment.	High
18.	H28.1.1 (2)	Improve the biocide quality based on annual water quality analysis.	High
19.	H29.2.2 (1)	Set up a hard barricade around the electrolyzer stack area.	High
20.	H29.2.2 (2)	Install a thermal resistance cover for the module cell as the barrier between workers and equipment.	High
21.	H01.3.3 (1)	Install a high-pressure trip function at the buffer storage vessel to shut down the unit and close inlet control valves.	High
22.	H01.3.3 (2) H02.3.1 (2)	Install vacuum insulations to maintain the low temperature of the storage.	High
23.	H01.3.3 (3)	Design the storage vessel as a doubled wall.	High
24.	H02.3.1 (1)	Install a temperature controller and trip function to avoid high temperatures in the storage vessel.	High
25.	H07.4.1 (1)	Deploy fixed or portable radiation monitors to monitor radiation levels in specific areas of the facility.	High
26.	H11.4.1 (1) H30.4.1 (1)	Conduct facility siting studies including minimum separation distance calculations, especially between the storage units and other hydrogen-containing equipment, as well as between these units and the nuclear power plant.	High
27.	H11.4.1 (2)	Blast-proofing the plant structure and building within the plant area.	High
28.	H15.4.1 (1)	Conduct a risk-based inspection (RBI) program.	High
29.	H15.4.1 (2)	Perform a material compatibility study for all the critical equipment and piping.	High
30.	H01.1.2 (1)	Install a high-pressure trip function at the demineralized water unit to send a signal to shut down the unit, closing feed water and steam inlet control valves.	Medium
31.	H04.2.1 (1)	Install a demineralized water buffer tank to ensure sufficient water supply for electrolyte generation.	Medium
32.	H04.2.1 (2)	Improve the make-up electrolyte supply system by installing the electrolyte buffer tank at the recycled electrolyte line.	Medium
33.	H05.3.1 (1)	Establish a continuous purging strategy and procedure for separator and vessels.	Medium
34.	H05.3.1 (2)	Control ignition sources at separators and vessel areas.	Medium
35.	H13.1.1 (1)	Install a ventilation system to remove any hydrogen leaked within the pump or compressors house.	Medium
36.	H13.1.1 (2)	Improve the rotating equipment design with friction resistance materials.	Medium
37.	H22.4.1 (1)	Improve the sewage system and design.	Medium
38.	H29.4.1 (1)	Trained personnel or workers on SSOW.	Medium
39.	H29.4.1 (2)	Use appropriate safety equipment for Working at Height (WAH), such as a full body harness with double lanyards.	Medium
40.	H01.2.2 (1)	Install demineralized water conductivity indicator and alarm at the inlet of the electrolyzer to monitor the quality and purity of demineralized water.	Medium
41.	H01.1.1 (1)	Install prefilters at the inlet of the feedwater line to capture impurities.	Medium
42.	H01.3.1 (1)	Develop a scheduled chemical cleaning for the demister or absorber.	Medium
43.	H01.3.1 (2)	Install a differential pressure (dP) indicator to detect early signs of demister clogging.	Medium
44.	H02.1.1 (1)	Install a pre-cooler at the inlet of the demineralized water unit to control the temperature of the steam supply.	Medium
45.	H02.1.1 (2)	Install a temperature controller at the feed water inlet.	Medium
46.	H02.2.1 (1)	Install a temperature controller to control the returned electrolyte flow.	Medium
47.	H02.2.1 (2)	Install a high temperature trip function at the electrolyzer module to shut down the unit.	Medium
48.	H03.2.1 (1)	Install a flow controller at the pump discharge line.	Medium
49.	H04.1.1 (1)	Configure a low flow trip function at the pump inlet line, to trip the pump motor at low flow.	Medium
50.	H04.1.1 (2)	Install the pump strainer at the pump inlet line.	Medium
51.	H04.1.2 (2)	Configure a critical parameter monitoring system at the steam supply line.	Medium
52.	H10.4.1 (1)	Establish a risk assessment specifically for the infrared (IR) inspection prior to work commencement.	Medium
53.	H12.4.1 (1)	Conduct assurance checks on maintenance quality.	Medium

(*Continued*)

Table 8. (Continued).

No.	Reference ID	Action Item	Risk Level/ Priority
54.	H25.4.1 (1)	Design a waste disposal area.	Medium
55.	H25.4.1 (2)	Perform assurance check on the waste management system.	Medium
56.	H25.4.1 (3)	Provide training to all relevant personnel on waste management.	Medium
57.	H20.4.1 (2)	Develop critical parameter indicators and monitoring for power supply.	Low

Table 9. Primary hazards and key recommendations.

No.	Hazards	Recommendations
1.	Hydrogen leakage, which can result in the accumulation of explosive mixtures.	(1) Install a high-pressure trip function that will automatically close and isolate the inlet valves and cut off the power to the hydrogen electrolysis unit in the event of high pressure. (2) Install an online hydrogen and oxygen analyzer at the outlet of the electrolysis module.
2.	High-voltage electricity.	(1) Install a high-voltage trip function at the outlet of the rectifier. (2) Install a high-pressure trip function that will automatically close and isolate the inlet valves and cut off the power to the hydrogen electrolysis unit in the event of high pressure.

Table 10. Sub-system #1 risk reduction.

Subsystem	SOEC electrolysis
FUNCTION	A high-temperature electrolysis process that uses ceramic-based solid oxide cells to split steam (H_2O) into hydrogen (H_2) and oxygen (O_2).
HAZARD	High Temperature
PRE-HAZID ANALYSIS	
Scenario	Increased temperature in electrolyzer stack during normal operation.
Cause	Inadequate circulation prevents efficient heat transfer from the electrolyzer stack.
Consequence	Electrolysis parts deteriorate and damage e.g., seals, membranes and electrodes.
Existing Safeguards	• Temperature indicators at the inlet and outlet of module cell. • Routine inspection and preventive maintenance. • Standard operating procedures.
Initial Risk Level	Medium
MITIGATION MEASURES	
Recommendations	(1) Install a temperature controller at returned electrolyte flow. (2) Install high-temperature trip function at the electrolyzer module.
POST-HAZID ANALYSIS	
Residual Risk Level	Low
ALARP Justification	(1) **Temperature controller** to regulates the returned electrolyte flow to ensure the temperature within safe operating limits, preventing overheating that could lead to material degradation, reduced efficiency, or safety events. (2) **High-temperature trip function** to automatically shut down the unit if temperatures exceed a critical threshold, preventing thermal runaway and protecting both people and assets.

Table 11. Sub-system #2 risk reduction.

Subsystem	Hydrogen Gas-Liquid Separator
FUNCTION	A hydrogen gas – liquid separator is used to separate entrained liquid from the hydrogen gas stream after electrolysis, prior to hydrogen purification.
HAZARD	Overpressure
PRE-HAZID ANALYSIS	
Scenario	Inefficient liquid removal due to clogged demister (mist eliminator) resulting in separator pressure increased.
Cause	Particulate contamination, build up and clog over time due to improper cleaning or backwashing.
Consequence	Hydrogen liquid or moisture carryover into the gas outlet and damaging the downstream equipment led to localized asset damage.
Existing Safeguards	• Routine inspection and preventive maintenance. • Pressure indicators to monitor pressure increment. • Pressure Relief Valves (PRVs) at the top of vessel.
Initial Risk Level	Medium
MITIGATION MEASURES	
Recommendations	(1) Develop a scheduled chemical cleaning for the demister or absorber. (2) Install a differential pressure (dP) indicator to detect early signs of demister clogging.
POST-HAZID ANALYSIS	
Residual Risk Level	Low
ALARP Justification	(1) **Scheduled chemical cleaning program** for the demister as proactive maintenance approach minimises the risk of fouling or blockage, reducing the likelihood of system failure or pressure build-up. (2) **Differential pressure (dP)** indicator across the demister enables continuous monitoring and provides early detection of clogging, allowing for timely intervention.

level, creating a safer operational condition and protecting both personnel and equipment from potential disasters.

Conclusion

This hazard analysis of pink hydrogen production, which involves integrating nuclear power with high-temperature electrolysis, has revealed several critical safety challenges that must be addressed for the technology to become viable at scale. The most persistent hazards identified include hydrogen leakage, due to its flammability and high dispersion rate, and high-voltage electricity, which increases the potential for system failures, particularly in close proximity to nuclear plants.

Although risk reduction measures significantly decreased the number of high-risk scenarios from 26 to just 2 scenarios, these remaining high-risk cases highlight the inherent difficulty of fully managing certain hazards within pink hydrogen systems. These persistent risks cannot be easily eliminated and require unconventional safety engineering controls, including advanced monitoring, automated safety mechanisms, and carefully coordinated system integration protocols.

For industry, this study highlights the need to adopt robust design practices, implement predictive maintenance tools, and invest in materials that are resistant to hydrogen embrittlement and thermal stress. For policymakers, it is essential to establish clear safety regulations specific to nuclear-hydrogen integration and to promote collaboration between the hydrogen and nuclear sectors.

Future research should incorporate quantitative risk-modeling techniques such as Fault Tree Analysis (FTA) and Failure Modes and Effects Analysis (FMEA) to gain a deeper understanding of potential failure mechanisms. Additionally, simulation-based stress testing under various operating conditions, along with on-site evaluations, can help identify hidden vulnerabilities and refine safety strategies.

In summary, although the majority of critical risk levels can be reduced through targeted interventions, pink hydrogen production still involves unresolved high-risk challenges. Addressing these will require continued research, innovation, and cooperation between stakeholders to ensure the long-term safety and viability of pink hydrogen technologies as part of a sustainable energy future.

Acronyms

AEM	Anion Exchange Membrane
ALARP	As Low as Reasonably Practicable
AWE	Alkaline Water Electrolyzer
ERP	Emergency Response Plan
ERT	Emergency Response Team
ESD	Emergency Shutdown
FMEA	Failure Mode and Effects Analysis
FTA	Failure Tree Analysis
HAZID	Hazard Identification
HIRA	Hazard Identification and Risk Assessment
HAZOP	Hazard and Operability Studies
HTSE	High Temperature Steam Electrolysis
LOC	Loss of Containment
LOPA	Layer of Protection Analysis
LTSE	Low Temperature Steam Electrolysis
PEM	Proton Exchange Membrane
PFD	Process Flow Diagram
PPE	Personal Protective Equipment
PRV	Pressure Relief Valve
RBI	Risk-based Inspection
SOEC	Solid Oxide Electrolysis Cells
SSOW	Safe System of Work
VCE	Vapor Cloud Explosion
WAH	Working at Height

Author contributions

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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