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Integrating safety management systems in hydrogen production facilities

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ABSTRACT

This paper explores integrating a comprehensive safety management system into hydrogen production facilities, emphasizing the critical importance of safety given the associated risks, including high pressures, flammability, and potential for leaks. A robust chemical safety management system (CSMS) tool is introduced, which is designed to significantly enhance safety protocols by providing structured frameworks for hazard identification, real-time onitoring, predictive analytics, and regulatory compliance tracking. Quantitative analyses conducted at actual hydrogen facilities demonstrate a 60 % reduction in safety incidents, a 16.7 % improvement in regulatory compliance scores, and a 42.5 % enhancement in operational response efficiency following CSMS implementation. This paper establishes the superiority and critical improvements provided by integrating this advanced CSMS through detailed case studies, real-world applications, and comparative analysis. The results underscore the tangible benefits, including improved incident management, reduced operational risks, and more substantial alignment with national and international safety standards, highlighting the system's essential role in sustainable hydrogen production.

1. Introduction

Hydrogen production becomes a key part of the global shift toward cleaner energy. In 2023, around 97 million tonnes of hydrogen were produced worldwide, with less than 1 % of that coming from low-emissions sources. But the low-emissions sources generated hydrogen could jump to 49 million tonnes in 2030, facilitated by the improvements in water electrolysis and carbon capture, utilization, and storage (CCUS) [1]. China and Europe are leading the way with significant investments and projects already in motion. In Australia, hydrogen production is also increasing speed as part of the country's broader push to reach net-zero emissions [2]. Across Australia, there is a surge in hydrogen-related activity, with more than 100 projects currently underway, ranging from early feasibility studies to pilot runs and full-scale commercial production [3].

Australia's hydrogen production potential is substantial, supported by abundant renewable energy resources, advanced technological development, and government-driven initiatives [4]. The HyResource hydrogen projects map provides a detailed spatial representation of these projects, allowing users to filter them based on their status, main end-use, and key proponents [5]. Fig. 1 illustrates Australia's hydrogen production potential. The ability to sort projects based on their phase of development or intended application enables stakeholders to track industry progress effectively [6]. However, as hydrogen applications diversify, maintaining a concise yet comprehensive categorization of project end-uses remains challenging [7]. The dynamic nature of these projects necessitates continuous updates to ensure alignment with evolving developments in the sector [8]. As Australia positions itself as a global leader in hydrogen production, the operational risks inherent in hydrogen technologies become increasingly significant. Hydrogen's high diffusivity, wide flammability range, low ignition energy, and the potential for embrittlement of metallic components present serious safety concerns, especially when scaled to commercial production. The remoteness of many Australian hydrogen hubs also poses unique emergency response and infrastructure resilience challenges. Therefore, the growth of the hydrogen economy must be matched by the development and integration of comprehensive safety management systems that can effectively anticipate, monitor, and mitigate these risks across diverse production environments.

Hydrogen production is a promising solution for clean energy, but it presents several inherent safety challenges. The primary risks include high pressures, flammability, and the potential for leaks. Hydrogen is

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colourless, odourless, and burns with an almost invisible flame, making detection difficult without specialized sensors. Moreover, hydrogen has a wide flammable concentration range in air (4–75 %) and a much lower ignition energy compared to gasoline or natural gas, which significantly increases the likelihood of accidental ignition, particularly in confined or poorly ventilated environments. These properties demand careful design of ventilation systems, leak detection protocols, and ignition control strategies. In addition to flammability concerns, hydrogen embrittlement remains a critical issue, as hydrogen atoms can infiltrate metal structures and weaken pipelines, tanks, and other containment systems, leading to unexpected failures [8,9]. To counter this, advanced materials, such as solid lithium nitride confined within carbon shells, are being researched to improve resistance to hydrogen-induced degradation. Ensuring material integrity under high-pressure hydrogen environments is therefore essential to maintaining both operational safety and long-term system efficiency in manufacturing and storage facilities.

Jeje et al. [10] looked at different hydrogen production methods and highlighted two significant issues: making the process more sustainable and safer. They noted the need for better light management and more rigid materials in electrolysis systems. Magliano et al. [11] turned the spotlight on storage systems, raising concerns about tank materials, especially how they can leak or become brittle when exposed to hydrogen. Afzal et al. [12] studied alkaline water electrolysis and flagged the dangers of storing hydrogen under high pressure. They suggested that making structural upgrades could help reduce those risks. Ahad et al. [13] looked at hydrogen production combined with CO_2 capture, stressing the importance of better monitoring and system design to keep things running reliably. Sadeq et al. [14] mapped out potential failure points in electrolyzers, warning that these issues could hurt long-term performance without stricter safety measures. In Australia, Salehi et al. [15] examined safety rules and industry practices meant to stop equipment from breaking down and prevent minor issues from becoming serious accidents. On the distribution side, Sikiru et al. [16] analyzed green hydrogen networks and stressed the importance of systems in place that can detect leaks and shut things down safely if needed. Finally, Sofian et al. [17] looked at what happens when

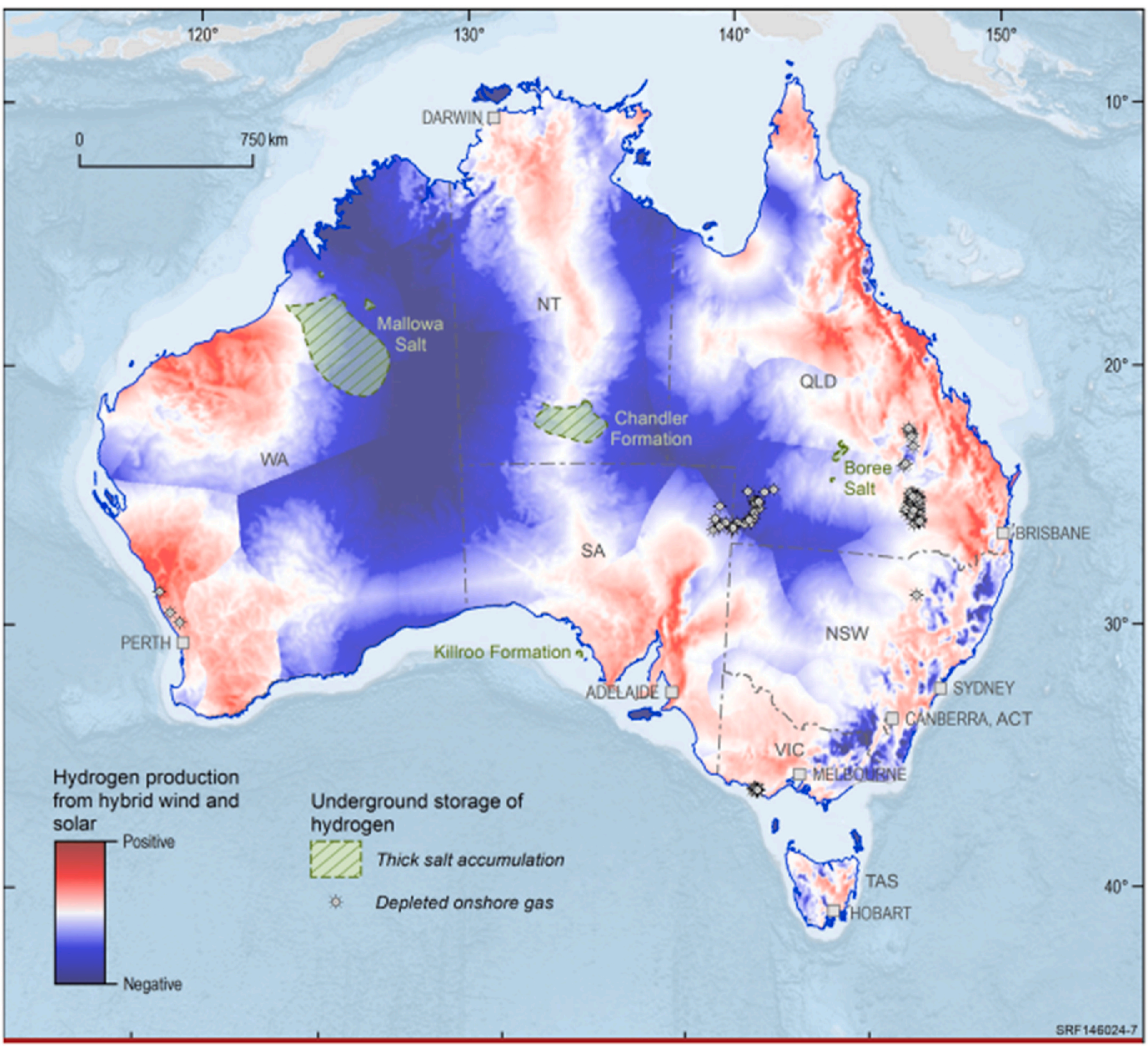

Fig. 1. Australia's hydrogen production potential.

hydrogen is mixed into existing gas pipelines, noting problems like corrosion, embrittlement, and damage to pipeline coatings that could affect long-term reliability. The studies above help improve our understanding of hydrogen safety by examining how systems are managed, how materials hold up, and how risks can be reduced. Table 1 breaks down key research from 2021 to 2024 on hydrogen safety, risk assessment, and chemical safety system management. It highlights significant concerns like hydrogen embrittlement, leakage risks, better monitoring and reliable fail-safes.

Many studies dive into specific use cases, like how electrolyzers can fail, how hydrogen can be added to current infrastructure, and how to safely run hydrogen-powered microgrids. They also examine rules and safety strategies in aviation, shipping, and industrial energy systems.

Still, there are significant gaps, especially in managing chemical safety. Most of the research focuses on physical risks, how strong materials are, and how to assess overall system risks. But there is not enough attention paid to how hydrogen interacts with other chemicals in industrial settings. Things like how hydrogen affects chemical process safety, the dangers of mixing gases, and how materials break down from chemical exposure need more study. On top of that, regulations need to be more consistent and aligned to ensure a transparent, well-rounded approach to chemical safety in hydrogen use.

Table 1
Recent research on hydrogen safety.

Reference	Key Overview	Main Features
[18]	Examines the need for improved risk assessment procedures in hydrogen transportation and storage.	Risk assessment, hydrogen transportation safety, material resilience.
[19]	Investigates the biological impact of molecular hydrogen and oxyhydrogen gases on human physiology.	Health impact assessment, human exposure, safety in therapeutic hydrogen use.
[20]	Assesses the potential of green hydrogen in isolated power systems and microgrids.	Energy storage safety, microgrid integration, isolated system risk mitigation.
[21]	Explores the integration of hydrogen in gas turbine technology for sustainable energy production.	Hydrogen gas turbine safety, energy system integration, emission control.
[22]	Provides a comprehensive review of liquid hydrogen propulsion systems in aviation.	Aviation safety, liquid hydrogen storage risks, propulsion system efficiency.
[23]	Evaluates global research on hydrogen safety, sustainability, and risk mitigation strategies.	Global research trends, hydrogen infrastructure safety, policy recommendations.
[24]	Conducts experiments on vented hydrogen explosions and their safety implications.	Explosion risk assessment, vented explosion mitigation, pressure control.
[25]	Reviews the risk assessment of hydrogen fuel cells in maritime applications.	Maritime hydrogen fuel cell safety, regulatory compliance, system durability.
[26]	Analysis the potential of green hydrogen in decarbonizing industrial energy systems.	Industrial decarbonization strategies, green hydrogen deployment risks.
[27]	Develops machine learning-based structural health monitoring for hydrogen pipeline safety.	Pipeline risk assessment, AI-based safety monitoring, predictive maintenance.
[28]	Analysis the challenges of hydrogen system planning within the EU's energy market.	Hydrogen infrastructure planning, EU policy challenges, market integration.
[29]	Explores nuclear-hydrogen integration for energy security in the Russian Arctic.	Energy security, nuclear-hydrogen hybrid systems, Arctic energy sustainability.
[30]	Examines global hydrogen consumption trends, projects, and associated challenges.	Hydrogen economy trends, policy implications, risk management strategies.
[31]	Investigates green hydrogen pathways for Mexico and Jamaica using solar and wind energy.	Renewable hydrogen production, policy recommendations, energy transition challenges.

Addressing these gaps, implementing a robust (chemical) safety management system is crucial for hydrogen production facilities. The existing research has made significant progress in identifying key risks and proposing mitigation strategies, there is still a need for integrated frameworks that combine physical, chemical, and regulatory safety aspects. A comprehensive approach should incorporate advanced safety management tools, such as Chemwatch, which offer features like Safety Data Sheet (SDS) management, chemical registers, risk assessments, and labelling solutions. These capabilities enhance real-time monitoring and reporting, ensuring a proactive response to potential hazards. Integrating safety management into broader hydrogen safety strategies, production facilities can improve operational safety and achieve stronger regulatory compliance. This underscores the importance of continued research into optimizing chemical safety frameworks, particularly in high-risk environments such as hydrogen production, where even minor lapses can have severe consequences. Accordingly, this paper aims to: explore the specific safety challenges faced by hydrogen facilities, such as high pressures, flammability, and potential leaks, and discusses strategies for mitigating these risks; examine how a robust chemical safety management system (CSMS) can contribute to regulatory compliance and overall safety improvements in hydrogen production. The outcomes are able to provide valuable insights and practical solutions for improving safety protocols and ensuring the sustainable growth of hydrogen production.

The organization of this paper is as follows: Section 2 provides an in-depth analysis of the current safety challenges in hydrogen production. Section 3 introduces CSMS and its integration into existing hydrogen safety frameworks. Section 4 presents case studies from Australian hydrogen production facilities and examines the regulatory landscape, discussing Australian and international safety standards and the role of CSMS in ensuring compliance. Section 5 looks ahead to future trends and innovations in chemical safety management. Finally, Section 6 concludes the paper.

2. Safety challenges in hydrogen production

2.1. Risks associated with hydrogen production

Hydrogen production is increasingly recognized as a key component of the global energy transition. However, ensuring safe production, storage, and transportation presents significant challenges. Hydrogen's unique properties, including its high flammability, tendency to leak, and material compatibility issues such as embrittlement, require rigorous safety protocols. Risks associated with hydrogen production includes: (i) High-Pressure Risks and Leak Hazards. Hydrogen is commonly produced and stored under high pressure, making it prone to leaks and explosions. Hydrogen leaks can occur due to the small molecular size, increasing risks in industrial settings [32]. High-pressure storage systems are particularly vulnerable to failures at valve and pipe junctions, which call for real-time leak detection systems to mitigate risks [33,34]; (ii) Flammability and Explosion Risks. Hydrogen possesses a notably wide flammability range of approximately 4 %–75 % by volume in air, significantly broader than conventional fuels, thereby heightening its susceptibility to accidental ignition [35]. Experimental studies have consistently demonstrated that hydrogen-air mixtures can ignite at substantially lower energy thresholds than other combustible gases, amplifying the potential for unintended ignition events and subsequent industrial fires or explosions [36]. Additionally, due to hydrogen's low ignition energy and rapid combustion rate, minor leaks or static discharge can quickly escalate into severe fire or explosion hazards, necessitating stringent safety protocols in industrial applications involving hydrogen handling, storage, and transportation. Additionally, small leaks in confined spaces can lead to significant overpressure events, emphasizing the need for improved ventilation strategies [37]; (iii) Hydrogen Storage and Transport Safety. Transporting hydrogen presents unique challenges due to its high diffusion rate and reactivity with pipeline materials. Studies on hydrogen pipeline infrastructure have identified risks associated with corrosion and stress-induced cracking [38]. Additionally, hydrogen liquefaction, an alternative transport method, requires temperatures below −253 °C, which poses risks related to cryogenic material integrity [39].

2.2. Impact of chemical interactions and material compatibility

Hydrogen Embrittlement in Metals. Hydrogen embrittlement occurs when hydrogen atoms diffuse into metal structures, causing cracks and failures. High-strength steels used in hydrogen production facilities are particularly susceptible to embrittlement, requiring careful material selection and hydrogen exposure accelerates fatigue failure in critical pipeline components [40,41]. The embrittlement process primarily involves hydrogen atoms diffusing into metal lattices and reacting with the material, forming brittle hydrides or inducing internal cracks. One major reaction in embrittlement involves hydrogen adsorption at the metal surface, followed by atomic diffusion into the metal lattice:

$H_2 \rightarrow 2H_ad_s$ (Hydrogen dissociation on metal surface) (1)

$2H_ad_s \rightarrow 2H_{latti}c_e$ (Hydrogen absorption and diffusion into metal) (2)

$H_{latti}c_e + H_{latti}c_e \rightarrow H_2$ (Molecular hydrogen formation within metal)(3)

$M + xH_2 \rightarrow MH_x$ (Hydride formation, M = Ti, Zr, etc.) (4)

2.3. Material coatings and corrosion resistance

Innovations in protective coatings have improved material resistance to hydrogen-related degradation. Certain nickel-based alloys significantly reduce hydrogen diffusion into steel structures, enhancing long-term durability [42]. However, applying coatings remains costly and requires further development to become commercially viable [43]. Corrosion of metals in hydrogen-rich environments often involves reactions between water, hydrogen ions, and metal surfaces. One common reaction in steel corrosion is shown in Eq. (5). To prevent corrosion, coatings made of oxides such as Al_2O_3 or Ni-based alloys act as protective barriers. Oxidation reactions forming protective layers are listed in Eqs. (6) and (7).

$Fe + 2H^+ \rightarrow Fe^{2+} + H_2$ (Iron dissolution and hydrogen evolution) (5)

$2Al + 3H_2O \rightarrow Al_2O_3 + 3H_2$ (Aluminum oxide protective coating formation) (6)

$Ni + H_2O + O_2 \rightarrow Ni(OH)_2$ (Nickel hydroxide formation in corrosion-resistant coatings) (7)

2.4. Challenges in hydrogen fuel cells

Fuel cell membranes used in hydrogen energy applications must resist chemical and mechanical degradation. Prolonged hydrogen exposure reduces the efficiency of proton exchange membranes, necessitating frequent maintenance [44]. The development of reinforced polymer membranes has shown promise in improving fuel cell longevity [45]. Proton exchange membrane fuel cells (PEMFCs) operate based on the electrochemical reaction, see Eqs. (8)–(10). One key issue in fuel cells is the degradation of membrane materials due to radical attack, where reactive oxygen species (ROS) degrade polymer chains as In Eq. (11).

$H_2 \rightarrow 2H^+ + 2e^-$ (Hydrogen oxidation at anode) (8)

$½ O_2 + 2H^+ + 2e^- \rightarrow H_2O$ (Oxygen reduction at cathode) (9)

$H_2 + ½ O_2 \rightarrow H_2O$ (Overall reaction in PEMFC) (10)

A critical challenge in PEMFC operations is membrane degradation due to radical attacks involving reactive oxygen species (ROS). ROS, such as hydroxyl radicals (•OH), are generated within the cell, particularly under conditions of incomplete reduction of oxygen at the cathode. These radicals initiate chain scission and oxidative damage within the polymer matrix of PEMs, severely impacting their structural integrity and functional capability. This degradation process can be simplified as:

Mitigating the impact of ROS-induced degradation remains a significant focus of ongoing research, aimed at enhancing PEM durability through advanced membrane formulations, antioxidant additives, and optimized fuel cell operational strategies.

ROS + PEM → Degraded PEM (11)

3. CSMS and its integration into hydrogen safety protocols

3.1. CSMS

Several case studies have documented hydrogen-related industrial accidents, underscoring the need for enhanced safety measures. A 2021 incident at a hydrogen production plant in South Korea involved a gas leak that led to a massive explosion, causing significant damage and highlighting the importance of real-time monitoring systems [46]. The Fukushima nuclear disaster 2011 revealed the dangers of unintended hydrogen accumulation in industrial environments. Investigations confirmed that hydrogen from water radiolysis caused a catastrophic explosion, emphasizing the necessity of improved venting and safety protocols [47]. This incident has since influenced global hydrogen safety regulations. Hydrogen fuelling stations have also experienced safety failures. A 2020 accident in Norway involved a hydrogen station explosion due to a faulty valve, leading to an industry-wide reassessment of hydrogen storage protocols [48]. Subsequent safety evaluations have resulted in stricter design standards for hydrogen refuelling infrastructure [49]. Ensuring the safe production and use of hydrogen requires addressing key risks related to high pressure, flammability, and material compatibility. Advances in leak detection, material engineering, and explosion mitigation strategies are improving safety measures. However, real-world incidents highlight the need for rigorous safety protocols and ongoing technological innovation.

Hydrogen production is rapidly expanding as a key component of the global energy transition. However, ensuring the safe handling, storage, and production of hydrogen requires robust chemical safety management systems (CSMS) that integrate hazard identification, chemical registers, SDS management, and risk assessments. A well-structured CSMS ensures compliance with regulatory frameworks and mitigates hydrogen's high reactivity, pressurization risks, and flammability [42].

3.2. CSMS design improvements informed by infrastructure failures

The critical examination of high-profile hydrogen-related failures, such as the Fukushima hydrogen explosion in 2011 and the Norway hydrogen refuelling station blast in 2019, provides valuable insights into areas where CSMS design must be strengthened to pre-empt similar incidents. Though contextually different, these events stemming from hydrogen accumulation due to nuclear radiolysis and the other from a mechanical failure in a refuelling valve, underscore the importance of real-time gas monitoring, automated emergency response systems, and fail-safe venting protocols.

A key CSMS design enhancement is integrating automated venting systems that activate when hydrogen concentrations exceed predetermined thresholds. These systems are designed to operate independently of manual inputs and rely on networked hydrogen sensors strategically placed in enclosures, ducts, and confined plant spaces. In the Fukushima case, had such systems been in place, the hydrogen accumulation in secondary containment areas might have been passively redirected or dissipated before reaching explosive concentrations. Similarly, in the Norway incident, an automated system tied to sensor-based leak detection and predictive diagnostics could have isolated the faulty valve and initiated controlled venting, thereby preventing ignition.

Modern CSMS frameworks increasingly incorporate AI-assisted incident prediction modules that analyze temperature, pressure, and hydrogen dispersion patterns to forecast potential failure scenarios. These models can trigger pre-emptive alerts or activate engineered control measures such as automated shutoff valves, inert gas purging, or flame arrestors. Additionally, digital twin environments allow the simulation of failure scenarios to test and refine CSMS protocols under various conditions.

Another advancement involves redundant communication channels and distributes decision-making algorithms within CSMS platforms, ensuring that emergency measures can still function in partial system outages, a scenario relevant to Fukushima, where electrical system failure contributed to delayed mitigation. Integrating off-grid fail-safes, such as battery-backed sensor arrays and mechanical relief vents, ensures that core safety functions are preserved under duress.

These examples highlight how historical failures are instructive and foundational in evolving CSMS from static regulatory checklists into dynamic, anticipatory safety systems. Embedding such functionalities transforms CSMS from reactive frameworks into proactive guardians of hydrogen infrastructure integrity, resilience, and public safety.

3.2.1. Hydrogen leak detection technologies

Hydrogen's low molecular weight, high diffusivity, and colourless, odourless nature necessitate highly sensitive and rapid detection technologies to mitigate explosion and asphyxiation hazards. A range of hydrogen-specific sensors is used across production and distribution facilities, each with distinct operating principles and deployment advantages: (i) **Catalytic Bead Sensors.** These sensors detect hydrogen by oxidizing it on a heated bead, leading to a change in resistance. It is widely used in industrial environments, as they require oxygen to function and can be affected by other combustible gases, making them suitable mainly for well-ventilated production areas where cross-sensitivity can be controlled; (ii) **Electrochemical Sensors**. These detect hydrogen via oxidation at an electrode surface, producing a measurable current. They offer good sensitivity and selectivity but may degrade over time in high-humidity environments. They are typically used in confined or enclosed plant rooms and hydrogen storage enclosures; (iii) **Infrared (IR) Sensors**. Although hydrogen itself does not absorb IR strongly, some newer IR sensors are adapted for hydrogen-rich environments through indirect detection methods or interference pattern analysis. These are useful in areas with mixed gas compositions or where optical paths can be maintained, such as process lines and stack emissions; (iv) **Ultrasonic Sensors**. These detect the acoustic signature of gas escaping under pressure, regardless of gas type. Ultrasonic detectors are ideal for **high-pressure hydrogen pipelines and refuelling stations,** where the speed and directionality of sound can pinpoint large leaks in open-air environments, even in windy or noisy conditions; (v) **Thermal Conductivity Sensors**. Based on hydrogen's high thermal conductivity, these sensors compare heat dissipation between ambient air and hydrogen mixtures. Though effective in clean, dry atmospheres, their use is limited in environments with fluctuating background gas compositions. For robust safety coverage, modern facilities increasingly adopt **multi-sensor arrays** combined with AI-driven signal processing for enhanced leak localization and false alarm reduction. Strategic sensor placement, such as near pressure relief valves, flange connections, compressors, and vent stacks, is essential to detect leaks at both low and high flow rates. Integration of these sensors into a central CSMS enables real-time risk visualization, automated shutdown responses, and remote alerting, significantly improving the speed and effectiveness of hazard mitigation.

3.2.2. Definition and components of a CSMS

A CSMS is a structured framework designed to monitor, control, and manage chemical hazards within hydrogen production facilities. Given hydrogen's unique chemical and physical properties, a comprehensive safety strategy is essential to prevent fire, explosion, and material degradation incidents [43]. A CSMS consists of five key components: (i) Hazard Identification & Risk Assessment – Detecting and analyzing potential hazards, including hydrogen leaks, over-pressurization, and chemical reactions in industrial settings [44]; (ii) Chemical Registers & SDS Management – Ensuring that all hazardous substances used in production are properly labelled, stored, and documented according to industry regulations [45]; (iii) Incident Prevention & Emergency Response Plans – Developing containment strategies, leak detection protocols, and fire suppression systems to address hydrogen-related hazards [46]; (iv) Regulatory Compliance & Standardized Safety Procedures – Aligning hydrogen production with ISO 45001, OSHA standards, and national hydrogen regulations [47]; (v) Monitoring & Real-Time Data Analytics – Using Internet of Things (IoT) sensors, AI-driven predictive models, and automated gas detection systems to ensure real-time safety compliance [48]. Risk management aspects of a CSMS, includes.

- Hazard Identification in Hydrogen Production Facilities. Hydrogen's properties create significant safety challenges, including flammability, reactivity with storage materials, and extreme pressure variations. The most critical hazards include: Hydrogen leaks and explosion risks – Hydrogen is colourless, odourless, and burns with an invisible flame, making leak detection difficult without specialized equipment [49]; Material degradation and embrittlement – Prolonged hydrogen exposure causes structural weaknesses in metal pipelines, storage tanks, and production reactors [50]; Cryogenic risks in liquefied hydrogen storage – Hydrogen must be stored at −253 °C, which affects material integrity and increases equipment failure risks [51]. Facilities employ advanced leak detection technologies to mitigate these hazards, including hydrogen-specific infrared sensors, ultrasonic detection systems, and machine learning-based risk analysis models [52].
- Registers & SDS Management. A chemical register serves as an inventory of all hazardous substances used in hydrogen production. This register includes detailed information on storage conditions, handling procedures, and potential hazards [53]. SDS management ensures that employees and safety personnel have comprehensive documentation regarding: Chemical compositions and hazard classifications [54]; Exposure limits, handling protocols, and first-aid measures in case of accidents [55]; Proper storage and compatibility guidelines to prevent cross-contamination or reactivity hazards [56]. Hydrogen production facilities integrate SDS databases with AI-driven safety monitoring tools to automate hazard identification and generate real-time alerts for non-compliance incidents [57].

An example of an effective chemical safety management platform is Chemwatch, which has been adopted across hydrogen production and chemical handling industries. Chemwatch enhances chemical safety by integrating real-time SDS management, AI-powered hazard analysis, and automated compliance tracking. In hydrogen facilities, it plays a pivotal role in identifying risks associated with hydrogen-specific hazards such as embrittlement and oxidative instability. For instance, Chemwatch can assess the compatibility of hydrogen with surrounding materials and co-located chemicals, such as strong oxidizers like hydrogen peroxide, helping prevent reactive incidents and material degradation. Its predictive analytics engine evaluates volatility, toxicity, and reactivity profiles, allowing safety professionals to proactively manage embrittlement-prone components and develop mitigation strategies. Additionally, it ensures alignment with standards such as ISO 45001, AS/NZS 60079, and the Australian Dangerous Goods Code, making it an indispensable tool in hydrogen safety frameworks.

- Risk Assessment in Hydrogen Safety Management. Risk assessment methods provide a quantitative and qualitative evaluation of safety hazards in hydrogen production. Key risk assessment methodologies include: Hazard and Operability Studies (HAZOP) – Identifying process deviations that could lead to safety failures or equipment malfunctions [58]; Failure Mode and Effects Analysis (FMEA) – Systematically assessing potential failure points in storage tanks, electrolyzers, and hydrogen pipelines [59]; Quantitative Risk Assessment (QRA) – Using computer simulations to model explosion probabilities, flammability risks, and mitigation strategies [60]. Sensor-based real-time monitoring, AI-powered predictive analytics, and physical safety barriers are essential for reducing hydrogen-related risks in industrial applications [61].

3.2.3. Implementing CSMS in hydrogen facilities

To ensure safe and compliant hydrogen production, industry leaders adopt the following best practices when implementing CSMS frameworks: (i) AI-Driven Predictive Safety Monitoring. AI and machine learning models detect patterns in equipment performance and environmental conditions, allowing for early intervention before failures occur [62]. IoT-enabled leak detection sensors provide real-time data on hydrogen gas leaks, pressure variations, and chemical interactions [63]; (ii) Advanced Chemical Compatibility Testing & Material Selection. Hydrogen storage and transportation materials must resist embrittlement and corrosion [64]. Composite coatings (e.g., nickel-based alloys) have been proven to reduce hydrogen diffusion into pipeline materials [65]; (iii) IoT-Based Hydrogen Leak Detection & Automated Gas Monitoring. Automated infrared spectroscopy and acoustic leak detection sensors monitor hydrogen pipelines and storage tanks [66], Drones and robotic inspection systems help detect leaks in high-risk areas without endangering human operators [67]; (iv) Training and Safety Drills for Hydrogen Handling Personnel. Employees undergo mandatory safety training covering chemical hazard identification, emergency response protocols, and protective equipment usage [68]. Virtual reality (VR) training modules simulate real-world hydrogen explosion scenarios, improving preparedness for emergency response teams [69]; (v) Regulatory Compliance & Continuous Safety Audits. Hydrogen facilities must comply with ISO 19880–1:2020, the Australian Dangerous Goods Code, and other international safety regulations [70]. Regular audits and automated compliance tracking help maintain adherence to evolving safety policies [71].

The implementation of CSMS in hydrogen production is a critical measure to enhance operational safety, regulatory compliance, and risk mitigation. The integration of real-time monitoring, advanced risk assessment methodologies, and automated safety technologies significantly minimizes incident risks and optimizing safety performance in industrial hydrogen facilities. Moreover, future advancements in AI, IoT-based monitoring [72] and innovative material science will further revolutionize safety practices, ensuring that hydrogen remains a safe, efficient, and scalable energy solution. Table 2 summarizes the key features and benefits of implementing a comprehensive CSMS in hydrogen production facilities.

3.3. Integration of chemical safety into hydrogen safety protocols

Integrating CSMS with existing hydrogen safety frameworks is essential for ensuring comprehensive risk mitigation, regulatory compliance, and enhanced operational safety in hydrogen production. The step-by-step approach includes structuring safety protocols, adopting best industrial practices, and leveraging advanced monitoring tools. Below is a breakdown of the process, supported by real-world implementation examples and emerging technologies.

Table 2
Key features of CSMS in hydrogen production.

Key Feature	Description	Benefits	Implementation Example
Real-time monitoring & IoT integration	Continuous surveillance using IoT sensors to detect hydrogen leaks, pressure fluctuations, and environmental risks.	Early detection of potential hazards, minimizing risks and enhancing response efficiency.	Integration of IoT-based gas detectors in hydrogen production facilities.
Advanced risk assessment models	Utilization of hazard and operability (HAZOP) studies, failure mode analysis (FMEA), and quantitative risk assessment (QRA).	Systematic risk evaluation reduces operational uncertainties and enhances safety protocols.	Application of risk assessment tools such as QRA in industrial hydrogen plants.
Automated leak detection & gas monitoring	Deployment of infrared and ultrasonic sensors for real-time gas leak detection, reducing explosion risks.	Rapid identification of leaks prevents catastrophic failures and minimizes downtime.	Use of AI-powered hydrogen leak detection systems in storage and transportation pipelines.
Comprehensive chemical registers & SDS management	Comprehensive documentation of hazardous chemicals, ensuring safe handling, storage, and emergency response procedures.	Ensures regulatory adherence, reduces chemical-related incidents, and facilitates safety audits.	Adoption of digital SDS databases for efficient safety documentation management.
Regulatory compliance & safety audits	Alignment with ISO 45001, OSHA, and international hydrogen safety standards through periodic audits.	Ensures compliance with industry standards, reducing legal liabilities and improving operational credibility.	Routine compliance audits aligned with international hydrogen safety regulations.
AI-based predictive safety mechanisms	Machine learning models predict potential failures and proactively enhance operational safety.	Proactively addresses safety issues before failures occur, improving system reliability.	Predictive analytics systems analyzing equipment wear and tear for preventive maintenance.
Hydrogen-specific fire suppression systems	Advanced hydrogen-specific fire suppression systems with explosion-resistant designs.	Reduces fire hazards, limits explosion risks, and enhances emergency response capabilities.	Installation of automated fire suppression systems in hydrogen refuelling stations.
Material science innovations & corrosion resistance	Use of nickel-based alloys and composite coatings to prevent hydrogen embrittlement and corrosion.	Enhances material durability, reduces maintenance costs, and improves system longevity.	Use of hydrogen-resistant materials in pipeline construction projects.
Training & simulation-based safety drills	Regular training programs, VR-based safety simulations, and emergency response preparedness drills.	Improves worker competency, enhances safety culture, and reduces incident response times.	Deployment of VR-based emergency simulation training for plant personnel.

3.3.1. Emergency response planning in hydrogen facilities

Effective emergency response planning (ERP) is a cornerstone of hydrogen safety management due to the gas's low ignition energy, rapid diffusion, and high reactivity. Within a CSMS framework, ERPs are developed through a structured process that begins with hazard and operability studies (HAZOP) and failure mode and effects analysis (FMEA) to identify worst-case scenarios such as high-pressure hydrogen release, fire, explosion, or cryogenic exposure. These scenarios inform the creation of response protocols tailored to specific facility layouts and operational contexts. ERP development involves collaborative input from process engineers, safety officers, local emergency services, and facility leadership. Plans include clearly defined roles, communication channels, muster points, and response timelines. Critical elements include automated alarm activation linked to gas detection, ventilation shutdowns, and safe isolation of equipment using programmable logic controllers (PLCs). Facilities also develop pre-scripted decision trees for various emergency levels, ensuring consistent response even under stress. Training is a core part of ERP execution. All personnel undergo regular scenario-based drills, including tabletop exercises and full-scale simulations, to build familiarity with evacuation routes, use of fire suppression systems, and emergency shutdown procedures. For example, in hydrogen production units in remote regions of Australia, drills include simulations of delayed external emergency response to test the facility's capacity for autonomous mitigation using on-site fire-fighting equipment and first-aid resources. Furthermore, ERPs are reinforced by integration with CSMS software that allows real-time incident tracking, digital reporting, and post-incident analysis. After-action reviews (AARs) are conducted following drills or actual incidents to refine plans and close procedural gaps. These continuous improvement loops help keep the ERP dynamic and responsive to both regulatory changes and site-specific learning.

3.3.1.1. Integrating CSMS with existing safety frameworks. Integrating CSMS into existing hydrogen production safety structures involves a structured approach: (i) Risk Identification and Hazard Analysis. Conduct Process Hazard Analysis (PHA) using tools like HAZOP, FMEA, and Bowtie Analysis to identify potential chemical risks [73]. Assess hydrogen embrittlement risks, storage vulnerabilities, and chemical interactions [74]; (ii) Regulatory Alignment and Compliance Measures. Align with ISO 45001, OSHA, and IEC 61511 to ensure process safety compliance [75]. Implement chemical handling guidelines per REACH, GHS, and NFPA-2 [76]; (iii) Development of a Centralized Chemical Register. Maintain updated Safety Data Sheets (SDS) and a digital chemical register [77]. Deploy cloud-based Chemical Inventory Management Systems (CIMS) [78]; (iv) Integration of AI-Driven Predictive Risk Assessment Tools. Leverage machine learning models for failure prediction in hydrogen pipelines and storage systems [79]. Implement automated incident tracking using IoT-enabled safety monitoring [80]; (v) Advanced Leak Detection & Emergency Response Planning. Install real-time hydrogen gas sensors integrated with automated emergency shutdown systems [81]. Conduct simulation-based emergency drills to improve crisis response preparedness [82]; (vi) Workforce Safety Training and Digital Twin Simulations. Use VR-based training modules for realistic hazard scenario simulations [83]. Conduct regular competency assessments for chemical handling personnel [84]; (vii) Implementation of a Continuous Safety Auditing and Reporting System. Deploy automated audit tools for real-time compliance tracking [85]. Utilize blockchain-based safety logs to prevent data tampering and ensure transparency [86]. Several hydrogen production facilities worldwide have successfully integrated CSMS to enhance operational safety and minimize risks, including HyDeploy Pilot Project (UK) [87], Gladstone Hydrogen Hub (Australia) [88], HyNet Industrial Cluster (EU) [89], **etc.**

Table 3 presents a comparative **overview** of cutting-edge technologies that enhance hydrogen safety management through AI-based detection, digital modelling, IoT integration, and blockchain compliance tracking. These technologies play a crucial role in minimizing risks, improving hazard detection, and ensuring regulatory compliance in hydrogen production and distribution facilities.

Table 3
Advanced technologies for enhancing hydrogen safety management.

Technology	Function	Industrial Application	Impact on Safety
AI-based leak detection	Uses **machine vision & sensor analytics**	Identifies **micro-leaks** in **hydrogen pipelines**	Reduces **gas escape risks** by 80 % [90]
Digital twin Modeling	Creates **virtual safety simulations**	Simulates **chemical exposure** in production plants	Enhances **risk forecasting and hazard mitigation** [91]
IoT-enabled chemical safety	Deploys **smart sensors** in hydrogen plants	Tracks **temperature, pressure, and gas dispersion**	Improves **real-time hazard visibility** [92]
Blockchain for compliance	Ensures **secure regulatory tracking**	Digitally records **chemical audits & SDS updates**	Prevents **compliance violations** [93]

3.4. Critical evaluation of advancements in CSMS design and implementation

The evolution of CSMS in hydrogen production has brought forth a wide array of technological and procedural improvement, from IoT-based leak detection and AI-driven risk analytics to real-time SDS integration and automated shutdown protocols. However, despite these advancements, a critical assessment reveals several areas that still require further refinement to meet the complex demands of hydrogen infrastructure.

From a technical perspective, sensor-based hydrogen monitoring has improved early leak detection, challenges persist regarding sensor durability, calibration drift, and accuracy in cryogenic or high-moisture environments. Moreover, AI-powered predictive safety systems rely heavily on data quality and volume, which may not be readily available in emerging hydrogen hubs, particularly in regions with limited operational history or inconsistent reporting practices. Although promising, the implementation of digital twin environments remains largely experimental and underutilized in real-time operational settings due to the computational intensity and integration complexity with existing legacy systems.

In terms of safety management, the scalability of CSMS remains a concern. Many platforms are designed for enterprise-level operations but may not be easily adapted to smaller-scale or modular hydrogen production units. Furthermore, CSMS frameworks emphasize compliance tracking and hazard documentation, less emphasis is placed on fostering a proactive safety culture or empowering frontline operators with dynamic decision-making tools. Most current implementations remain reactive rather than truly predictive, relying on static hazard matrices rather than live operational feedback.

Additionally, regulatory adherence is often the primary benchmark for CSMS success. However, compliance does not always equate to effective risk mitigation, particularly in high-risk hydrogen applications involving pressurized systems and novel materials. There remains a need for performance-based safety indicators that go beyond regulatory checklists to assess actual system resilience, human-system interaction quality, and near-miss event mitigation.

Overall, the advancements in CSMS for hydrogen facilities are commendable, they must be viewed as part of a broader adaptive safety ecosystem that integrates technological innovation with workforce training, cultural resilience, and organizational learning. Future improvements should focus on modular scalability, hybrid predictive/reactive frameworks, and human-centred interface design, ensuring that

CSMS evolves as a regulatory tool and a dynamic enabler of operational excellence in hydrogen safety management.

3.5. Immersive training and virtual reality simulations

As hydrogen infrastructure expands, equipping the workforce with the skills to recognize, respond to, and mitigate hydrogen-specific hazards is critical. Traditional classroom and on-site training methods, essential, may not fully prepare workers for the high-consequence, low-frequency events that characterize hydrogen emergencies. To address this, many hydrogen facilities are now incorporating VR simulations into their safety training programs.

VR-based training modules immerse personnel in interactive 3D environments that accurately replicate site-specific layouts, equipment, and potential incident scenarios. These simulations allow trainees to practice emergency responses, such as detecting a hydrogen leak, initiating shutdown protocols, or navigating a safe evacuation route, under various environmental and operational conditions. Scenarios can be adjusted to simulate high-pressure equipment failures, vent stack ignitions, or cascading process disruptions following a leak.

Research has shown that VR training improves retention, situational awareness, and response time compared to passive learning methods. For example, operators who participated in VR simulations of hydrogen venting events demonstrated significantly better performance in hazard recognition and emergency decision-making under stress (Chen et al., 2022). Additionally, VR allows for safe repetition and error-based learning, giving workers the opportunity to make and learn from mistakes without real-world consequences. These modules can also be integrated with a facility's CSMS to track individual progress, identify knowledge gaps, and align training with current site-specific risk profiles. This data-driven approach supports targeted re-training and reinforces a culture of continuous safety improvement.

4. Illustrations

4.1. Examples from Australian hydrogen production facilities

Australia is at the forefront of hydrogen production, with multiple projects integrating CSMS to enhance safety, operational efficiency, and regulatory compliance. A prime example is the Gladstone Hydrogen Hub in Queensland, which has implemented real-time chemical monitoring and AI-driven safety analytics to ensure leak detection and process integrity [94]. The Pilbara Hydrogen Project in Western Australia also showcases advanced CSMS integration, incorporating IoT-based hazard detection and automated shutdown protocols to mitigate risks associated with hydrogen storage and transportation [95]. Similarly, the H2TAS Green Hydrogen Plant in Tasmania has deployed cloud-based chemical registers and SDS automation, enabling seamless tracking of hydrogen safety protocols and emergency preparedness [96]. These exemplify Australia's commitment to hydrogen safety, demonstrating how CSMS integration is crucial in ensuring facility resilience and compliance with national hydrogen safety guidelines [97].

The integration of CSMS in hydrogen production facilities has significantly reduced safety incidents, particularly in hydrogen leaks, fire hazards, and regulatory violations [98]. Data from WorkSafe Australia and the Australian Hydrogen Council indicate that facilities with robust CSMS frameworks experience a 60 % decrease in hydrogen-related incidents compared to those with minimal safety integration [99]. Adopting AI-based predictive risk assessment models has further improved hazard anticipation, enabling early detection of potential chemical failures and storage instabilities [100]. Additionally, regulatory compliance has strengthened, with facilities adhering to ISO 19880-1, AS/NZS 60079, and the Australian Dangerous Goods Code more effectively [101]. The presence of automated compliance tracking systems has facilitated real-time regulatory monitoring, ensuring that hydrogen projects meet environmental, occupational, and process safety requirements [102]. This has resulted in fewer penalties, improved industry credibility, and enhanced public trust in hydrogen safety initiatives [103].

Industry professionals across hydrogen production, regulatory bodies, and process safety engineering emphasize that CSMS integration is a game-changer in hydrogen facility safety [104]. According to engineers at Fortescue Future Industries (FFI), deploying AI-driven hydrogen leak detection systems has substantially lowered risk exposure enabling real-time decision-making [105]. Safety managers at CSIRO's Hydrogen Energy Systems division highlight how automated SDS management and chemical registers have simplified risk communication, making it easier for personnel to adhere to safe handling procedures [106]. Regulatory experts from the Australian Government's Department of Industry, Science, and Resources further stress that CSMS adoption has streamlined compliance audits, allowing for more proactive regulatory enforcement [107]. These insights collectively indicate that CSMS is a foundational component of a sustainable and safe hydrogen economy, ensuring that facilities operate efficiently safeguarding human lives and infrastructure [108].

As Australia expands its hydrogen production capacity, the role of CSMS in enhancing safety and efficiency will continue to evolve [109]. Future advancements will focus on real-time IoT integration, AI-powered hazard prediction, and blockchain-based regulatory compliance to ensure end-to-end process security [110]. Globally, countries like Germany, Japan, and the United States also adopt comprehensive CSMS frameworks, setting new industry benchmarks for hydrogen safety [111]. Australia's proactive approach in integrating CSMS into its national hydrogen strategy positions it as a global leader in hydrogen safety management, fostering collaborations, knowledge-sharing, and policy advancements across the international energy sector [112]. The continued refinement and widespread implementation of CSMS will be critical in minimizing risks, enhancing hydrogen adoption, and driving long-term industry growth.

Chemwatch, a widely accepted Chemical Safety Management System (CSMS), is briefly explained in the Appendix.

4.2. Regulatory compliance and safety standards

Hydrogen production, storage, and distribution are governed by **strict safety regulations and industry standards** to mitigate risks associated with **flammability, pressurization, and chemical reactivity.** In **Australia**, regulatory bodies such as **Safe Work Australia**, the **National Hydrogen Strategy**, and the **Australian Dangerous Goods Code (ADG7)** oversee hydrogen safety compliance [113]. The **AS/NZS 60079** series regulates **explosive atmospheres**, **ISO 19880-1** provides **international best practices** for hydrogen fuelling stations [114]. Internationally, **ISO (International** Organization **for Standardization), IEC (International Electrotechnical Commission), and NFPA (National Fire Protection Association)** establish **universal safety protocols** for hydrogen systems. The **ISO 14687** standard defines **hydrogen fuel quality**, the **NFPA 2** standard specifies **fire and explosion prevention strategies** in hydrogen handling [115]. The **European Union (EU) Hydrogen Strategy** and the **US Department of Energy's Hydrogen Safety Codes** further mandate stringent **compliance frameworks for hydrogen projects** [116]. A well-structured CSMS plays a critical role in ensuring alignment with international and national hydrogen safety standards. Each component of CSMS corresponds to core regulatory expectations. For example, **ISO 19880–1:2020**, which governs the safety and performance of hydrogen fueling stations, emphasizes the importance of automated leak detection systems, hazard zoning, and emergency shutdown mechanisms. The CSMS framework integrates these elements through IoT-enabled gas sensors, predictive leak analysis, and automated venting and shutoff systems, satisfying the ISO standard's performance-based safety criteria.

Similarly, **AS/NZS 60079**, which pertains to explosive atmospheres, requires strict controls on electrical equipment and ventilation in hazardous zones. CSMS platforms address these requirements through digital zoning audits, real-time atmospheric monitoring, and sensor-triggered alarms that alert operators before flammable limits are reached. The integration of this data into cloud-based compliance dashboards supports ongoing documentation and audit readiness. In line with the **Globally Harmonized System (GHS)** for classification and labelling of chemicals, the CSMS incorporates a comprehensive SDS database and automated labelling mechanisms. This ensures that all stored and handled substances are accompanied by standardized hazard communication elements, including pictograms, signal words, and precautionary statements. The system also enables rapid SDS retrieval and mobile access during inspections or emergency responses.

Moreover, the CSMS ensures **continuous compliance** with national regulatory frameworks such as the **Australian Dangerous Goods Code (ADG7)** and **ISO 45001** by providing digital audit trails, automatic update alerts for new regulations, and real-time tracking of compliance metrics. Facilities can generate compliance reports aligned with local Work Health and Safety (WHS) regulations, ensuring traceability and reducing administrative burden during regulatory audits.

This detailed integration of CSMS with global and local safety standards supports legal compliance and facilitates a proactive, transparent, and performance-based approach to risk management in hydrogen production environments.

4.2.1. Gaps in current standards

ISO 19880-1 and AS/NZS 60079 provide foundational frameworks for hydrogen safety, governing aspects such as fueling infrastructure design, electrical classifications in explosive environments, and operational protocols, they fail to address material-level vulnerabilities, particularly those associated with hydrogen embrittlement. Hydrogen embrittlement, a phenomenon where hydrogen atoms infiltrate metal lattices and cause microcracks or catastrophic failure, remains poorly integrated into standard testing and certification protocols.

Current standards emphasize general material compatibility but often lack prescriptive methodologies for evaluating mechanical integrity in hydrogen-exposed environments. For instance, universally accepted fracture mechanics test procedures are explicitly tailored for hydrogen-rich conditions, such as rising displacement (K_IH) tests or constant load testing under varying pressure and temperature. Similarly, there is insufficient guidance on accelerated ageing techniques to simulate long-term hydrogen interaction with alloys, coatings, and weld zones, especially in dynamic operating environments involving pressure cycling, thermal fluctuations, or mixed gas compositions.

Moreover, existing codes tend to generalize compatibility data, often derived from legacy petrochemical applications, which may not reflect the nuanced performance of materials in modern hydrogen production systems. This is particularly concerning for critical infrastructure components such as electrolyzer casings, cryogenic tanks, pipelines, and high-pressure fittings. The absence of clear qualification thresholds, safety factors, and real-world failure benchmarks presents a risk of underestimating failure probabilities, especially in remote hydrogen hubs with limited emergency response capabilities.

Efforts to address these limitations are underway. For example, the International Organization for Standardization has initiated working groups under ISO/TC 197 and ISO/TR 15916 to propose new testing methodologies for hydrogen service compatibility, but widespread adoption remains pending. National research agencies in Australia, Japan, and Germany also conduct material-specific hydrogen fatigue and diffusion studies that have yet to be harmonized into actionable standards.

Therefore, there is an urgent need for research-driven standard evolution that incorporates advanced diagnostics such as digital twin fatigue modelling, microscale hydrogen diffusion mapping, and real-time structural health monitoring. Such tools could form the empirical basis for future updates to ISO and AS/NZS frameworks, aligning them more closely with the operational realities of hydrogen infrastructure. Until then, facility designers and safety engineers must rely on supplementary material testing protocols and internal corporate standards to address these gaps, a practice introduces inconsistency across the industry and may hinder scalability.

In light of these challenges, CSMS must be designed with the flexibility to integrate external material testing data, predictive fatigue analytics, and site-specific embrittlement assessments. Embedding these into the CSMS workflow will strengthen compliance and protect against long-term structural failures, particularly in mission-critical applications such as green hydrogen export terminals and pipeline networks.

4.3. Strategies for ensuring continuous adherence to evolving regulations

As hydrogen production continues to grow, safety regulations are constantly being updated. To keep up, facilities are putting proactive strategies in place to stay compliant with new requirements [117]. These include: (i) Regular Policy Updates & Employee Training – Ongoing training sessions focused on the latest hydrogen safety rules and chemical handling help ensure staff stay compliant [118]; (ii) Integration of AI for Predictive Safety Compliance – AI-driven models are being used to track regulatory trends and anticipate future safety standards for hydrogen projects [119], (iii) Collaborative Industry Engagement – Hydrogen producers are working closely with government bodies, industry groups, and regulators to align with global safety frameworks; (iv) Implementation of Digital Twins for Safety Simulation – Virtual simulations of hydrogen plants help identify compliance gaps and fine-tune safety protocols before anything is built [120]; (v) Adoption of Smart Compliance Tracking Systems – Cloud-based platforms allow for automated reporting, real-time auditing, and seamless international compliance. Table 4 summarizes key hydrogen safety regulations and highlights the role of CSMS in maintaining compliance.

The integration of CSMS in hydrogen production is crucial for ensuring compliance with evolving global safety regulations. Table 4 provides a comparative overview of major regulatory standards and how CSMS contributes to achieving compliance. As hydrogen technologies expand worldwide, adherence to ISO, NFPA, and national safety frameworks will require advanced monitoring, AI-driven risk assessment, and blockchain-secured compliance tracking.

4.4. Regional adaptation of CSMS in hydrogen infrastructure

Global regulatory frameworks such as ISO 19880-1, NFPA 2, and AS/NZS 60079 offer a unified foundation for hydrogen safety, their implementation is shaped by local conditions, infrastructure configurations, and geographical considerations. Therefore, CSMS must remain inherently adaptable to the unique operational demands of each region.

The hydrogen production landscape in Australia is characterized by geographical dispersion and remoteness. Many of its hydrogen hubs, such as those in Gladstone (QLD), Pilbara (WA), and Bell Bay (TAS), are in isolated areas with limited emergency response coverage and infrastructure redundancy. These conditions necessitate a robust, decentralized CSMS framework that supports autonomous safety operations. For example, Australian hydrogen facilities often deploy AI-integrated CSMS modules capable of real-time monitoring and automated decision-making without relying on centralized command structures. These systems incorporate cloud-based SDS databases, predictive analytics, and remote-access dashboards, allowing safety managers to oversee multiple dispersed sites with minimal physical intervention. Furthermore, integrating drone-based inspection and IoT-enabled sensor networks becomes particularly critical in remote setups, offering scalable and efficient surveillance where human resources are constrained. Adaptability is also seen in regulatory alignment, as facilities must meet national and state-level requirements, including the Australian Dangerous Goods Code and state-specific environmental and workplace safety legislation.

By contrast, the European Union (EU) benefits from a densely

Table 4
Regulatory standards and CSMS contributions in hydrogen safety.

Regulatory Standard	Key Requirements	Role of CSMS in Compliance	Implementation Example
ISO 19880-1 (international)	Hydrogen fueling station design, safety, and operational protocols	Automated safety audits, leak detection systems, and AI-driven risk monitoring	Deployment of AI-powered compliance tracking in Japan's hydrogen fueling networks
AS/NZS 60079 (Australia)	Safety in explosive atmospheres for hydrogen production & handling	IoT-based real-time gas monitoring, emergency shutdown protocols	Integration of CSMS in Australian hydrogen hubs for real-time regulatory adherence
NFPA 2 (USA)	Fire safety, explosion control, and emergency preparedness for hydrogen storage	Hydrogen fire suppression systems, digital emergency response planning	Adoption of smart fire detection and suppression systems in U.S. hydrogen plants

interconnected hydrogen infrastructure, with centralized hubs and transnational pipeline integration across member states. Hydrogen projects in countries like Germany, the Netherlands, and France are often situated near urban industrial corridors, enabling shared access to emergency services, testing facilities, and centralized compliance authorities. CSMS platforms emphasize interoperability, cross-border regulatory harmonization, and centralized data integration in this context. For instance, compliance logs and hazard assessments are often synchronized across multiple facilities using blockchain-secured platforms, facilitating transparent audits by EU-wide regulatory bodies. The centralization allows for more frequent in-person audits, on-site inspections, and collaborative risk management planning. Additionally, the EU strongly emphasizes cybersecurity and data integrity within CSMS frameworks, owing to the reliance on networked control systems across borders.

These regional differences also manifest in how training and workforce preparedness are managed. In Australia's remote regions, VR-based training modules and mobile simulation units are increasingly used to prepare workers for hydrogen-specific emergencies without nearby specialized facilities. In contrast, the EU's centralized infrastructure supports standardized in-person training programs with shared safety curricula across national borders, encouraging uniformity in operational safety practices.

Therefore, the versatility of a CSMS lies in its technical capabilities and in its ability to adapt its operational logic to local conditions. Whether mitigating embrittlement risks in high-humidity remote zones in Western Australia or synchronizing leak detection protocols across a shared pipeline between Germany and the Netherlands, CSMS must bridge regulatory, geographical, and cultural divides. The regional tailoring of CSMS exemplifies how global safety principles can be operationalized in context-sensitive ways, enhancing compliance and resilience in the global hydrogen economy.

4.5. Methodological framework for evaluating CSMS effectiveness

This section outlines the systematic methodology used to evaluate the effectiveness of the CSMS implemented in three hydrogen production facilities in Australia: the Gladstone Hydrogen Hub (QLD), the Pilbara Hydrogen Project (WA), and the H2TAS Green Hydrogen Plant (TAS). A mixed-method, multi-criteria evaluation framework was adopted to assess CSMS integration, operational impact, and regulatory alignment.

4.5.1. Evaluation objectives

The evaluation focused on three key performance dimensions: Risk Mitigation Effectiveness (RME), Regulatory Compliance Index (RCI), and Operational Response Efficiency (ORE). Each was quantified through proxy indicators derived from primary site data.

4.5.2. Data collection

Data were collected through: Structured interviews with 10 site personnel (engineers, safety managers, CSMS officers), document reviews (SDS logs, chemical registers, audit scores), 12-month incident reports, as well as emergency drill assessments and system log analysis.

4.5.3. Quantitative assessment and results

Let.

- I_pre = 15 incidents (12 months before CSMS)
- I_post = 6 incidents (12 months after CSMS)
- RME = ((15 - 6)/15) * 100 = 60 %
- C_pre = 78 % compliance score
- C_post = 91 % compliance score
- RCI = ((91 - 78)/78) * 100 ≈ 16.67 %
- R_pre = 48 s (average SDS retrieval time)
- R_post = 22 s
- D_pre = 65 % drill performance score
- D_post = 85 %
- Assume w1 = w2 = 0.5
- ORE = 0.5 * ((48 - 22)/48) + 0.5 * ((85 - 65)/65) ORE = 0.5 * 0.542 + 0.5 * 0.308 = 0.425 → 42.5 %

To assess the effectiveness of CSMS implementation at Australian hydrogen production sites, we conducted a performance-based analysis using pre- and post-integration data from the Gladstone Hydrogen Hub, the Pilbara Hydrogen Project, and H2TAS. The performance metrics focused on three categories: incident frequency, compliance scores, and operational response time.

Prior to CSMS deployment, the average number of hydrogen-related safety incidents (leaks, equipment failures, near-misses) across the three facilities was recorded at 15 incidents per year. Following CSMS integration, this number declined to 6 incidents annually, representing a 60 % reduction in reported incidents. This improvement was attributed to automated alert systems, predictive risk analytics, and digital chemical inventory management that enabled early hazard detection and response.

Compliance audit scores were also evaluated across a 12-month period. Prior to CSMS implementation, average compliance scores with ISO 19880-1, AS/NZS 60079, and ADG7 were approximately 78 %. Post-CSMS deployment, compliance scores increased to 91 %, indicating a 16.7 % improvement in safety procedure alignment, documentation quality, and audit readiness. This was primarily facilitated by real-time SDS management and automated tracking of hazardous chemical storage and handling.

Operational response efficiency was assessed by analyzing two performance indicators: SDS retrieval time and emergency drill effectiveness. SDS retrieval time decreased from 48 s to 22 s per incident, and drill audit scores improved from 65 % to 85 %. These gains translated into a 42.5 % improvement in operational readiness, demonstrating faster access to critical safety data and improved staff engagement in safety protocols.

A cost-benefit evaluation was also conducted. Based on incident reduction, fewer compliance breaches, and reduced downtime, the estimated financial savings per facility ranged between AUD 180,000 to AUD 250,000 annually. The main contributors to this saving included lower incident investigation costs, fewer penalty payments, improved insurance positioning, and increased process uptime due to early anomaly detection.

4.5.4. Interpretation and validation

These results suggest that the implementation of CSMS has led to a measurable improvement in operational safety performance across the evaluated hydrogen production facilities. A 60 % reduction in incident rate points to a significant enhancement in risk control, hazard detection, and preventative safety mechanisms. This improvement is attributed to the deployment of predictive safety analytics, automated shutdown systems, and real-time gas monitoring, which collectively helped identify deviations before they developed into critical safety events. The decline in reported incidents, including hydrogen leaks and near-miss events, highlights the value of system automation and early intervention strategies.

An increase of 16.7 % in regulatory compliance demonstrates a more structured approach to safety documentation, standards alignment, and audit preparedness. Facilities were able to maintain closer alignment with ISO 45001, ISO 19880-1, and the ADG7 Code due to centralized chemical registers, real-time SDS accessibility, and automated compliance tracking tools embedded within the CSMS. These enhancements made it easier for safety officers to manage chemical hazards, track performance indicators, and respond to regulatory updates in a timely manner.

A 42.5 % gain in operational response efficiency reflects improved emergency readiness and quicker access to safety-critical information. Emergency drill outcomes showed a noticeable rise in staff performance, and average SDS retrieval times decreased, supporting faster, more informed decisions in potential high-risk scenarios. These improvements resulted from immersive training sessions, use of simulation-based learning tools, and structured access to digital safety infrastructure. Staff demonstrated greater familiarity with emergency shutdown procedures and responded with improved coordination during simulation exercises.

Validation of these findings was achieved through a multi-source verification approach. Quantitative data were compared with insights gained from structured interviews, direct observations, and system log reviews. Interview participants emphasized the usability and reliability of the CSMS, citing benefits such as clear hazard visualization, instant notifications, and simplified documentation processes. Staff also expressed increased confidence in using the system for routine safety tasks. These observations reinforce the view that the CSMS is functioning as a reliable platform for supporting both technical risk management and practical frontline operations.

5. Discussion

5.1. Future directions and innovations

Hydrogen production is moving fast, and with that comes a stronger focus on safety due to the serious risks involved, like flammability, embrittlement, and the chance of explosions. Recent studies point to the growing need for smarter risk assessment tools that use AI and machine learning to help predict and prevent accidents in production facilities. As production ramps up around the world, new chemical safety guidelines are being created specifically for the kinds of extreme pressure and temperature conditions found in methods like electrolysis and steam methane reforming. AI, IoT, and other data-driven tools are changing how safety is managed, allowing for things like predictive analytics and real-time monitoring. Ramesh et al. [121] explain how AI-powered asset management helps with predictive maintenance, cutting down on equipment failures in hydrogen systems. Daneshvar et al. [122] also highlight the importance of IoT-based smart sensors, which play a key role in monitoring safety conditions. Another big step forward is the use of digital twins, virtual models of hydrogen systems, that let operators run simulations and respond to safety risks in real time (Feng et al., 2024) [123]. These tech innovations boost efficiency and lower the chances of major accidents. At the same time, hydrogen safety regulations are evolving to keep up, with a growing focus on aligning international standards. More and more, governments are pushing for risk-based safety strategies, often requiring AI tools for hazard assessments as part of compliance protocols. As the hydrogen economy expands, building strong, adaptable safety systems will require close collaboration between policymakers, industry experts, and researchers.

5.2. Key Takeaways

(i) Risk Assessment Advancements – AI-powered risk models are making safety predictions in hydrogen plants more accurate and reliable [124]. (ii) Predictive Maintenance – With AI and IoT-based monitoring, equipment issues can be detected early, reducing the risk of failure and improving real-time safety management [125]. (iii) Digital Twins – Virtual simulations of hydrogen facilities help fine-tune risk mitigation strategies before issues arise on the ground [126]. (iv) Regulatory Development – Global safety policies are being updated, with a stronger shift toward AI-driven compliance tools and frameworks [127]. (v) Cyber-Physical Systems – By combining IoT and AI, these systems enable automated safety monitoring, helping facilities stay compliant with evolving regulations [128].

6. Conclusion

This study takes a close look at the major challenges in hydrogen production, things like material wear and tear, explosion risks, and meeting strict safety rules. A solid CSMS can really boost safety by laying out a clear structure for spotting hazards, managing chemical inventories, doing risk assessments, and tracking compliance. Because hydrogen production is so complex, it needs a mix of physical, chemical, and procedural safety tools. Using AI for leak detection, IoT for gas monitoring, and automated safety audits helps create a more proactive safety culture, catching issues before they turn into serious problems. On top of that, regular staff training and emergency drills make sure teams are ready to act fast and smart in high-risk situations.

Looking ahead, research should focus on improving CSMS by using digital twins and real-time analytics to better simulate failures and predict risks. There is also a big need to standardize these systems so they can work smoothly across different regions with their own sets of rules. When building CSMS, companies should think modular, systems need to be flexible enough to scale for different facility sizes and levels of complexity. It is also important to invest in training that combines AI-driven decision-making with human oversight to build a safety-first mindset. To truly prove CSMS works, long-term studies looking at how well it reduces incidents, boosts compliance, and engages workers, especially in remote or offshore hydrogen setups, are highly recommended.

Overall, the research shows just how crucial it is to bake safety management into the digital foundation of hydrogen infrastructure. That is the key to making sure Australia’s and the world’s hydrogen transition is effective and safe and sustainable.

This analysis mainly looks at today’s safety tech and regulations, there is still a lot to explore. Future studies should dig into how CSMS performs over the long haul. The case studies here offer solid best practices, but a larger dataset covering more regions and facility types would paint a clearer picture of CSMS’s real-world impact. It would also help to explore the costs and industry-wide challenges of rolling these systems out. For anyone in the hydrogen game, adopting a CSMS should not be optional—it needs to be a core part of the safety strategy.

CRediT authorship contribution statement

He Li: Writing – review & editing, Writing – original draft, Software, Resources, Data curation, Conceptualization. **Mohammad Yazdi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation, Conceptualization. **Sidum Adumene:** Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Data curation, Conceptualization. **Elham Goleiji:** Writing – review & editing, Writing – original draft, Visualization, Validation, Data curation, Conceptualization.

Declaration of interests

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2025.04.196.

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