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Review

Proactive Regulation for Hydrogen Supply Chains: Enhancing Logistics Frameworks in Australia

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Abstract: The rapid growth of Australia's hydrogen economy highlights the pressing need for innovative regulatory strategies that address the distinct characteristics of hydrogen supply chains. This study focuses on the supply-side dynamics of the hydrogen energy sector, emphasizing the importance of tailored frameworks to ensure the safe, efficient, and reliable movement of hydrogen across the supply chain. Key areas of analysis include the regulatory challenges associated with various transportation and storage methods, particularly during long-distance transport and extended storage periods. The research identifies notable gaps and inconsistencies within the current regulatory systems across Australian states, which inhibit the development of a unified hydrogen economy. To address these challenges, the concept of Proactive Regulation for Hydrogen Supply (PRHS) is introduced. PRHS emphasizes anticipatory governance that adapts alongside technological advancements to effectively manage hydrogen transportation and storage. The study advocates for harmonizing fragmented state frameworks into a cohesive national regulatory system to support the sustainable and scalable expansion of hydrogen logistics. Furthermore, the paper examines the potential of blockchain technology to enhance safety, accountability, and traceability across the hydrogen supply chain, offering practical solutions to current regulatory and operational barriers.

Keywords: blockchain technology; energy policy; hydrogen supply chain; proactive regulation

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1. Introduction

Hydrogen energy is rapidly emerging as a cornerstone of the global energy transition, offering a clean, versatile and sustainable alternative to fossil fuels. As the most abundant element in the universe, hydrogen produces only water when used as a fuel, making it a zero-emission energy source with immense potential to decarbonize multiple sectors of the global economy [1]. Recent technological advancements and declining production costs for green hydrogen, generated through renewable energy-powered electrolysis, have accelerated its adoption worldwide [2]. Over 30 countries have released hydrogen roadmaps and strategies, collectively committing more than $70 billion in public funding to hydrogen initiatives. Major economies like the European Union, Japan, South Korea and the United States have introduced aggressive targets for hydrogen production and use, reflecting its potential to revolutionize energy systems, reduce greenhouse gas emissions, and stimulate economic development [3].

Australia, with its abundant renewable resources and established energy infrastructure, has emerged as a prominent player in the global hydrogen economy [4]. The 2024 National Hydrogen Strategy outlines a vision to position Australia as a global leader by 2030, building upon the 2019 foundation. Its four key objectives [5] are:

(1) developing globally cost-competitive hydrogen supply,
(2) driving domestic decarbonization,
(3) ensuring community benefit, and
(4) enabling trade through strategic investment and partnerships.

The strategy identifies key applications for hydrogen, including its use in fuel-cell vehicles, shipping, energy storage, and as a feedstock for zero-carbon fuels like ammonia and methanol.

Despite this momentum, Australia's hydrogen development faces regulatory barriers. Existing frameworks, largely adapted from natural gas and hazardous materials regulations, are poorly suited to hydrogen's unique characteristics, including its low density, high leak potential, and wide flammability range [6,7]. These misalignments create inefficiencies and uncertainty for developers. In addition, Australia's federal structure causes fragmented regulatory responsibilities across the states, further complicating the project development and scaling.

This paper explores these challenges by analyzing the current regulatory landscape for hydrogen transportation and storage in Australia. It identifies critical gaps and inconsistencies within existing frameworks and proposes forward-thinking regulatory approaches. Central to this analysis is the concept of proactive regulation for hydrogen supply (PRHS), which advocates for anticipatory governance that evolves alongside technological advancements. Through an examination of emerging hydrogen projects in Australia and comparisons with international best practices, it highlights practical regulatory challenges and outlines pathways for reform. Emphasis is placed on harmonizing state and federal policies in Australia to establish a cohesive regulatory framework. Addressing these issues is essential for setting a benchmark for the hydrogen economy.

2. Literature Review

Hydrogen production in Australia aligns with global practices, utilizing methods with varying environmental impacts. Green hydrogen is produced through the electrolysis of water powered by renewable energy sources such as wind and solar. This method is the most sustainable, generating no carbon dioxide emissions during production [6]. Blue hydrogen, derived from natural gas, incorporates carbon capture and storage technologies to reduce emissions, offering a lower-carbon alternative [7,8]. Conversely, grey or brown hydrogen, produced from fossil fuels without carbon capture and storage, emits significant carbon dioxide, making it the least environmentally friendly option [8]. These pathways reflect Australia's commitment to diversifying hydrogen production while addressing sustainability challenges [7].

2.1. Regulatory Challenges

Australia's ambition to become a global leader in the hydrogen market faces significant regulatory challenges that, if not addressed proactively, could hinder the industry's growth and investment potential. According to the Department of Climate Change, Energy, the Environment and Water (DCCEEW), regulatory certainty is a critical factor in attracting the investment needed to realize Australia's hydrogen export ambitions [5].

One key challenge is the lack of uniform nationwide standards and regulatory frameworks for critical aspects of the hydrogen supply chain, such as hydrogen transport and the design, configuration, and operation of refueling stations. This regulatory fragmentation creates uncertainty, increases costs, and diminishes investor confidence, posing significant barriers to the development of efficient supply chains for both domestic use and export markets [8]. Harmonized and forward-thinking regulatory frameworks are essential to enhancing market stability, reducing regulatory compliance costs, and positioning Australia as a global hydrogen powerhouse.

Storage infrastructure also presents complex challenges. Current dangerous goods regulations are often inadequate for large-scale hydrogen storage facilities [7]. Hydrogen's unique physical and chemical properties—such as its high propensity for leaks and combustion—exceed the safety requirements designed for traditional fuels like natural gas [7,9,10]. Comprehensive safety protocols, including advanced monitoring systems and robust emergency response plans, are necessary to mitigate risks associated with hydrogen's wide flammability range and low ignition energy.

The lack of targeted and harmonized regulations addressing these characteristics creates a dual risk for Australia. From a safety perspective, inadequate standards increase the likelihood of accidents, which could undermine public trust in hydrogen as a reliable energy source [7,10]. From an economic standpoint, the absence of clear regulatory guidelines discourages investment in critical storage infrastructure, as developers face uncertainty in meeting regulatory compliance requirements and ensuring the long-term durability of storage systems [11–13]. This regulatory gap could delay the deployment of large-scale hydrogen facilities, impeding Australia's ability to establish a robust hydrogen supply chain.

As Alsulaiman highlighted, these regulations should mandate the use of hydrogen-compatible materials, integrate advanced monitoring and leak detection systems, and establish stringent safety protocols for both high-pressure gaseous storage and cryogenic liquid storage [14]. The research explores potential hydrogen leakage scenarios and the associated regulatory challenges, emphasizing the importance of proactive measures. Addressing these issues can enhance investor confidence, accelerate infrastructure development, and strengthen Australia's position as a global leader in the hydrogen economy [13,14].

Table 1 outlines the hydrogen supply chain stages, identifying gaps in regulatory frameworks across resource inputs, processing, transport, storage, distribution, and end-use integration. The harmonization of standards is critical for advancing global hydrogen trade, facilitating clean energy transitions, and ensuring efficiency across diverse regions and sectors [11,13,14].

Table 1. Hydrogen energy supply chain.

Stage	Key Components & Processes
Input of Resources	Fossil fuels, Biomass, Renewable energy sources
Processing & Conversion	Steam methane reforming, Electrolysis, Gasification, Pyrolysis, Chemical carrier synthesis
Long-Distance Transport	Pipeline networks, Cryogenic tankers (liquid H_2), Ammonia shipping, (Liquid Organic Hydrogen Carrier) transport
Storage & Reprocessing	Underground salt caverns, Pressurized tanks, Ammonia cracking units, Carrier regeneration
Short-Distance Distribution	Tube trailer delivery, Gaseous pipeline networks, Mobile refuelers, Local storage buffers
End-Use Integration	Industrial refining, Power generation systems, Fuel cell vehicles, Heating network blending

2.2. State and Territory Legislative Advancements

Australia's National Hydrogen Strategy has catalyzed significant legislative and regulatory progress across states and territories, with each jurisdiction tailoring its approach to foster hydrogen industry growth [5]. For example, the Victorian Government enacted the Energy Legislation Amendment (Energy Fairness) Act 2021 [14], emphasizing hydrogen production safety and consumer protections. Victoria (VIC) also implemented the Renewable Hydrogen Industry Development Plan 2021 to support pilot projects and establish safety standards for integrating hydrogen into the energy grid. Similarly, New South Wales (NSW) introduced the Gas Supply (Safety and Network Management) Regulation 2022 [15], focusing on network management and safety protocols for hydrogen integration. The Victorian Government is leveraging its natural resources and capabilities to develop a robust hydrogen economy, progressing from pilot projects and localized hubs to interconnected regional activity centers and integrated supply chains, with a focus on sector coupling, market connectivity, and export opportunities [16].

Queensland (QLD) has taken a leading role in export-focused hydrogen development by amending its Gas Supply Act 2003 [17] through the Hydrogen Industry Development Amendment Act 2023, enabling hydrogen transportation via pipelines and supporting the establishment of export hubs like Gladstone [18,19]. These initiatives align with Australia's national hydrogen priorities, emphasizing renewable hydrogen for decarbonization, energy security, and export opportunities. Collaborative investments between government, industry, and research institutions further drive technological advancements and workforce development in leading states like VIC, QLD, and NSW.

Western Australia (WA) enacted the Petroleum Legislation Amendment Act 2024 [19] to regulate hydrogen exploration, aligning with its Renewable Hydrogen Strategy 2024–2030 [20]. South Australia (SA) introduced the Hydrogen and Renewable Energy Act 2023 and 2024 regulations to promote infrastructure development while ensuring ecological safeguards and community engagement. These measures prioritize green hydrogen production, renewable integration, and decarbonization while stimulating economic growth through job creation and export opportunities [21,22].

Tasmania (TAS) has leveraged its abundant hydropower resources to support its Renewable Hydrogen Action Plan, which includes industrial water access facilitated by the Water Miscellaneous Amendments Act 2023 [23,24]. The state's Bell Bay Green Hydrogen Hub exemplifies its commitment to developing hydrogen export capacity. Meanwhile, the Northern Territory (NT) focuses on solar-powered hydrogen projects like the Darwin H2 Hub, leveraging its proximity to Asian markets to reduce export costs and delivery times [25,26].

The Australian Capital Territory (ACT) integrates hydrogen policies into broader sustainability frameworks, such as the Climate Change Strategy 2019–2025 [27]. However, the ACT does not yet have a dedicated hydrogen strategy, as its focus remains on electrification and renewable electricity rather than hydrogen. In contrast, SA has implemented substantial legislative measures, such as the Hydrogen Action Plan 2019, to advance hydrogen production, distribution, and infrastructure development [28,29].

3. Methodology

This study combines structured desktop research with systematic policy analysis to identify key regulatory gaps and implementation challenges in Australia's hydrogen energy sector. Following the structured analytical framework illustrated in Figure 1, this investigation aims to deliver evidence-based insights and pragmatic recommendations that address regulatory compliance complexities while supporting the development of a harmonized regulatory framework enhanced by blockchain technology's security and traceability capabilities.

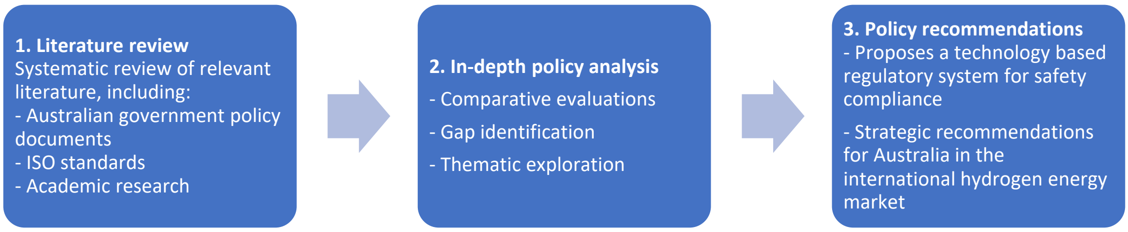

Figure 1. The research roadmap.

Desktop research formed the foundation of this study, involving the systematic review of literature and government policy documents related to hydrogen logistics and storage. Key sources included Australian government policy documents and regulatory frameworks, international standards and best practices for hydrogen operations (such as ISO standards) and academic research and industry analyses on hydrogen supply chains and safety considerations. This broad and diverse range of sources provided a strong basis for understanding the hydrogen policy landscape and identifying key challenges and opportunities [30].

The methodology for analyzing hydrogen energy policies across Australian states consisted of a structured, three-stage framework designed to ensure a comprehensive and actionable evaluation. The first stage focused on a thorough review of relevant policies. This included a systematic analysis of Australian government policy documents, international standards and both academic and industry research. By incorporating both domestic and global perspectives, this stage established a robust understanding of the existing policy landscape, highlighting key themes and identifying critical gaps [31]. This initial review provided the necessary foundation for a well-informed and comprehensive analysis.

The second stage of the methodology centered on detailed policy analysis. This involved evaluating current regulatory frameworks across Australian states and territories to identify similarities, differences and best practices. A critical aspect of this analysis was benchmarking against international regulations to ensure that Australia's hydrogen energy policies align with global standards and remain competitive in the international market. Additionally, this phase examined the implications of these policies for various stakeholders, including policymakers, industry participants and the public. By doing so, the analysis provided a thorough understanding of the strengths and weaknesses of existing frameworks and their impact on the development of Australia's hydrogen economy [32].

The final stage of the methodology was dedicated to developing policy recommendations based on the findings from the review and analysis stages. This phase involved an analysis to identify key issues such as regulatory compliance challenges. Using these insights, recommendations were formulated to address these challenges and improve the hydrogen energy policy framework [32,33]. The ultimate goal of this stage was to promote regulatory coherence across states and territories while fostering the growth of the hydrogen economy and aligning with Australia's ambitions to lead the global hydrogen sector.

This methodology is well-suited for analyzing hydrogen policies, as it addresses harmonization and inter-state complexity. By incorporating comparative analysis and benchmarking, the methodology ensures that Australia's policies are globally competitive. Moreover, its stakeholder-centered approach ensures that the recommendations are both practical and inclusive, addressing real-world challenges faced by the hydrogen industry. The progression from policy review to analysis and recommendations creates a logical framework for addressing inconsistencies and ensuring the country's success in the hydrogen economy [33].

The methodology also addressed the regulatory challenges facing the hydrogen sector, particularly the misalignment between rapid technological advancements and outdated regulations. Specific challenges in hydrogen transportation and storage were examined, including difficulties in maintaining hydrogen's physical integrity, the lack of harmonized technical standards and policy fragmentation between state and federal jurisdictions. These challenges emphasize the need for a unified regulatory approach to enable efficient and safe hydrogen supply chains.

This structured approach analyzes the hydrogen energy policies of Australia. By addressing the inter-state complexities and applying global benchmarks, the study aims to deliver recommendations that will enable Australia to overcome regulatory challenges and establish its success in the hydrogen economy. The qualitative approach allows for the exploration of complex, context-specific issues that may not be captured through quantitative methods [31].

4. Analysis

The analysis begins with a comprehensive policy review, synthesizing insights from Australian government documents, international standards, and academic research to identify foundational themes and gaps. The review also incorporates critical stages of the hydrogen supply chain as shown in Table 1, including input of resources and processing and conversion methods. The second stage, policy analysis, benchmarks state-level regulatory frameworks against international best practices, while examining the disparities among states and their implications for stakeholders. This stage is further informed by the complexities of long-distance transport, storage and reprocessing and short-distance distribution, highlighting infrastructure needs and logistical challenges. Finally, recommendations are developed to address barriers such as safety protocols, environmental regulatory compliance and scalability, while integrating innovations like blockchain for enhanced traceability. By incorporating the full spectrum of supply chain stages, this structured approach aligns with Australia's federal complexities and global decarbonization goals, fostering regulatory coherence.

4.1. Review of Policies

Hydrogen energy policies and legislative frameworks across Australian states and territories exhibit significant variations in priorities, infrastructure development and adoption of international standards, as shown in Table 2. For example, NSW has articulated its hydrogen ambitions through the NSW Hydrogen Strategy, 2021 [34], which emphasizes the establishment of hydrogen hubs and the integration of hydrogen into existing gas networks. However, while NSW partially aligns with ISO for hydrogen fuelling stations, the state still faces challenges in advancing its infrastructure for storage and distribution.

The adoption of international standards in Australia reflects broader global patterns. A comprehensive comparative study of regulations, codes and standards for hydrogen fuelling stations across countries—including the United States (California), United Kingdom, Italy, Germany, Canada and Nordic nations—revealed diverse approaches. Italy stood out with its nation-specific regulations for hydrogen fuelling stations, while most other countries relied heavily on international standards. In Europe, the standardization framework evolved in alignment with the regulation (EU) 2023/1804 on alternative fuels infrastructure deployment. The study identified critical risk control measures, particularly drawn from ISO, with safety protocols for unloading, storage, compression and cooling derived from established industrial practices. The study was targeted on countries that have already hydrogen fuelling stations and associated regulations: the USA (California), the United Kingdom, Germany, Italy, Canada, Sweden, Norway, Denmark and Spain. [30]. For Australia to enhance its hydrogen policies, harmonizing national standards, applying public-private partnerships, tailoring regional strategies and prioritizing safety and infrastructure development are essential. By learning from global practices, implementing performance metrics, fostering stakeholder collaboration and maintaining policy agility, Australia can strengthen its position in the global hydrogen economy.

VIC demonstrates full compliance with several international standard in governing hydrogen generation through electrolysis, but large-scale infrastructure for long-distance hydrogen transport and storage remains underdeveloped. In QLD, the QLD Hydrogen Industry Strategy 2019 [35] positions the state as a leader in hydrogen exports, with a focus on developing port infrastructure like the Gladstone export terminal. QLD aligns fully with ISO 14687 [36], which specifies hydrogen quality standards for various applications, including fuel cells. However, the state's hydrogen initiatives are largely export-focused [37].

SA stands out for its legislative support, including the Hydrogen Action Plan 2019 [29], the Hydrogen and Renewable Energy Act 2023 [21] and the Hydrogen and Renewable Energy Regulations 2024 [22]. These measures provide a comprehensive framework for hydrogen development, addressing safety, storage and renewable energy integration. SA also fully complies with ISO 19880 [38], focusing on hydrogen fuelling infrastructure and is a leader in hydrogen blending and underground storage initiatives among the states.

WA has prioritized large-scale green hydrogen production and expanded regulatory oversight to include hydrogen as a resource and an export. While WA indirectly follow international best practices, e.g., partially align with ISO 16111 [39], it covers hydrogen storage systems. Its focus remains on export-oriented infrastructure development, including pipelines and ports.

TAS's hydrogen initiatives use its abundant hydropower resources which support hydrogen production by addressing water usage for electrolysis. Compliance with ISO 16110 [40], which covers hydrogen production and safety, is partial and the state's geographic isolation poses challenges for transport and storage development.

The NT, still in the early stages of hydrogen development, has outlined its vision through the Renewable Hydrogen Strategy 2020 [25] and the Renewable Hydrogen Master Plan 2022 [26]. These initiatives focus on solar-powered hydrogen production in remote areas. However, there is no reported direct alignment with international standards such as ISO and the territory faces significant infrastructure and regulatory gaps.

The Australian Capital Territory (ACT) has not developed specific hydrogen policies or legislation. The Climate Change Strategy 2019–2025 [27] emphasizes electrification and renewable energy, such as wind and solar power, over hydrogen development. The ACT lacks direct alignment with any ISO standards and remains focused on renewable electricity for direct applications, such as electric vehicles and infrastructure, rather than hydrogen energy.

SA is the only jurisdiction with dedicated hydrogen legislation, while other states integrate hydrogen into broader energy frameworks. Largely compliance with ISO standards, such as ISO 14687 (hydrogen quality) [36] and ISO 19880 (fuelling stations) [38], is seen in QLD and SA, whereas other states demonstrate partial or no alignment. Export-focused states like QLD and WA lead in infrastructure development, while VIC and NSW concentrate on domestic applications like fuel cell vehicles and hydrogen blending. However, all jurisdictions face challenges in harmonizing safety regulations, adopting international standards and developing infrastructure for storage and transport.

QLD's Hydrogen Industry Strategy 2019 [35] demonstrates exemplary alignment with ISO 14687 for hydrogen fuel quality standards, creating a robust framework for its export ambitions. In contrast, TAS and NT exhibit significant regulatory gaps regarding ISO 16111 compliance for hydrogen storage safety protocols. This inconsistency across jurisdictions highlights Australia's fragmented approach to hydrogen regulation. The European Union offers an instructive counterpoint through its cohesive regulatory framework under Directive 2014/94/EU, which establishes uniform standards across member states. Adopting similar harmonization measures would strengthen Australia's competitive position in the global hydrogen market [36,38,39].

4.2. Policy Analysis

The hydrogen energy policies and legislation across Australian states and territories share some similarities in terms of their overarching goals, focus areas and challenges, despite regional differences in implementation. One of the most significant commonalities is the shared intent to improve environmental outcomes by using hydrogen as a clean energy source. This alignment is evident in strategies like the NSW Hydrogen Strategy 2021 [34], the Renewable Hydrogen Industry Development Plan 2021 of VIC [16] and QLD's Hydrogen Industry Strategy 2019 [35]. Each of these plans emphasizes the production of green hydrogen, which is derived from renewable energy sources, as a pathway to achieving environmental sustainability. VIC and NSW emphasize green hydrogen more explicitly in their strategies [16,34].

Infrastructure development is another area of convergence. Most states aim to build robust hydrogen production, storage and transport systems to support domestic and export markets. For instance, QLD and WA prioritize the development of export-oriented infrastructure, such as ports and pipelines, as part of their strategies. Similarly, SA leads in developing infrastructure for hydrogen blending into gas networks and underground storage, supported by the Hydrogen and Renewable Energy Act 2023 [21]. VIC and NSW, while focusing more on domestic applications, also highlight the need for infrastructure to support hydrogen refueling stations and integration into urban energy systems [16,34].

The ambition to export hydrogen energy is a notable similarity among states, particularly QLD, WA and SA [18,22,33]. These regions are well-positioned geographically and resource-wise to become major exporters of green hydrogen to international markets, especially in Asia. Australia's hydrogen export ambitions drive major investment in infrastructure and deepen trade ties with Asia. While offering opportunities for regional job growth and industry diversification, this focus may risk neglecting domestic hydrogen applications. Careful attention is needed to ensure environmentally sustainable use of land, water, and energy, along with robust certification systems to support global market integration.

Table 2. Comparative Analysis of Hydrogen Energy Policies and ISO Standards in Australia.

	Key Policy and Relevant Legislation Documents (Year)	ISO Standards Alignment	Observations About Hydrogen Energy Supply Chain Analysis
NSW	1. NSW Hydrogen Strategy 2021) [34] 2. Gas Supply (Safety and Network Management) Regulation 2022) [15]	ISO 19880. Gaseous hydrogen—Fueling stations. [38] (partial)	NSW has the need for improved hydrogen quality traceability, effective gas quality monitoring and enhanced stakeholder coordination [41]. It is establishing hydrogen hubs, promoting renewable energy verification, developing emergency procedures and incentivizing hydrogen adoption to create a robust and efficient supply chain [15,34,41].
VIC	1. Energy Legislation Amendment (Energy Fairness) Act 2021 [14] 2. Renewable Hydrogen Industry Development Plan (2021) [16]	ISO 22734: Hydrogen generators using water electrolysis—Industrial, commercial and residential applications. [42] (full)	The state needs to improve hydrogen energy products' traceability, stakeholder coordination, transparency, safety compliance and export readiness. Key issues include verifying renewable hydrogen origins, managing gas blending, utilizing incentives and integrating with energy markets [14,37,43]. Works related to community engagement and export infrastructure development are required for a competitive hydrogen economy [44].

Table 2. *Cont.*

	Key Policy and Relevant Legislation Documents (Year)	ISO Standards Alignment	Observations About Hydrogen Energy Supply Chain Analysis
QLD	1. QLD Hydrogen Industry Strategy 2019 [35] 2. Gas Supply Act 2003 [17]	ISO 14687: Hydrogen fuel quality—Product specification [36] (Largely)	QLD's hydrogen supply chain faces challenges in traceability, transparency, stakeholder coordination, gas blending verification, market integration and public trust. Its planned actions include certification systems, incentive tracking, supply chain development and community outreach to ensure renewable hydrogen authenticity, improve collaboration and align international standards for a sustainable hydrogen economy [35,45].
SA	1. Hydrogen Action Plan 2019 [29] 2. Hydrogen and Renewable Energy Act 2023 [21] 3. Hydrogen and Renewable Energy Regulations 2024 [22]	ISO 19880: Gaseous hydrogen—Fueling stations. [38] (Largely)	SA's hydrogen supply chain challenges include ensuring renewable hydrogen traceability, improving data transparency, fostering stakeholder collaboration, optimizing infrastructure and enhancing export readiness [19,20,34]. Key priorities also involve building public trust in hydrogen technologies and managing decentralized production for remote areas, aiming to support a competitive and sustainable hydrogen economy [45,46].
WA	1. Petroleum Legislation Amendment Act 2024 [19] 2. Renewable Hydrogen Strategy 2022 [20]	WA indirectly follows international best practices [20].	WA's hydrogen supply chain faces challenges in traceability, certification, data transparency, stakeholder coordination, infrastructure planning, export readiness and decentralized production. Key actions include Guarantee of Origin certificates, supply chain transparency, stakeholder collaboration and public awareness [20,47].
TAS	1. Water Miscellaneous Amendments Act 2023 [21] 2. Renewable Hydrogen Action Plan 2020 [22]	ISO 16110: Hydrogen generators using fuel processing technologies [40] (partial)	TAS's hydrogen supply chain faces challenges in traceability, data transparency, stakeholder coordination, infrastructure optimization, export readiness and public trust. Planned actions include certification development, infrastructure assessments, stakeholder engagement and community education [5,6]. Addressing these issues will support efficient production, robust supply chains and TAS's goal of becoming a global hydrogen leader [22].
NT	1. Renewable Hydrogen Strategy 2020 [25] 2. Renewable Hydrogen Master Plan 2022 [26]	-	NT faces challenges in cost competitiveness, infrastructure development, resource management, storage, export readiness, regulatory frameworks and public acceptance. [25,26] Planned actions, including resource assessments, infrastructure upgrades, regulatory reforms and industry engagement, aim to address these issues and position NT as a leader in renewable hydrogen production and export [5,6].
ACT	1. Climate Change Strategy 2019–2025 [27]	-	While the ACT focuses heavily on renewable energy, particularly solar and wind, its hydrogen energy initiatives are limited, as the region primarily relies on energy imports and has a smaller industrial base compared to larger states [4,6].

Common challenges faced by some states and territories include the lack of harmonized regulations and the fragmented adoption of international standards like ISO 14687 [36] and ISO 19880 [38]. While SA, VIC, and QLD demonstrate full compliance with some ISO standards, other jurisdictions, such as TAS and the NT, show only partial or no alignment. This lack of consistency creates barriers for cross-border and international collaboration. Another shared challenge is the high cost and complexity of hydrogen production, storage and distribution infrastructure, especially in regions with smaller economies or geographic constraints, such as the NT and TAS [47,48].

In summary, the similarities in hydrogen energy policies and laws across Australian states and territories include a collective environmental focus, an emphasis on infrastructure development, ambitions for hydrogen export and shared challenges related to regulation, standardization and cost barriers. Despite these shared goals and obstacles, the pace and scale of implementation differ.

On the other hand, the regulatory fragmentation carries significant implications for Australia's hydrogen economy. Without standardized safety protocols and quality specifications, interstate hydrogen transport becomes logistically complex and economically inefficient. Companies operating across multiple jurisdictions face increased compliance costs and administrative burdens, potentially deterring investment. The current patchwork approach also complicates certification for international export markets, where consistent quality assurance is paramount. Furthermore, the disparity in regulatory maturity between states creates uneven development opportunities, with QLD's export capabilities outpacing inland territories that lack comparable frameworks. A unified national approach would reduce these barriers and enable more coordinated infrastructure planning, creating economies of scale that individual state initiatives cannot achieve independently.

In addition, inconsistencies in hydrogen energy policies across Australian states create technical challenges in areas such as hydrogen quality standards, storage requirements, and transport protocols. Variations in safety regulations for hydrogen storage, such as high-pressure tanks in SA versus cryogenic systems in WA, hinder the development of standardized infrastructure. These discrepancies increase compliance costs for businesses and delay project timelines, as companies must navigate a patchwork of regulations. Ultimately, this regulatory fragmentation diminishes investor confidence in the hydrogen economy, making it more difficult to attract the necessary funding for large-scale projects. The lack of standardized infrastructure due to differing storage and transport requirements complicates the logistics of hydrogen distribution. For instance, if one state mandates high-pressure storage while another requires cryogenic systems, producers may need to invest in multiple types of infrastructure, which raises capital expenditure and operational costs.

4.3. Policy Recommendations

A review of regulatory documents on hydrogen transport and storage in Australia identified safety as a key theme. Due to hydrogen's flammability and low molecular weight, there is a critical need for strict safety standards to prevent leaks and accidents. The review highlights the importance of developing comprehensive, hydrogen-specific regulations to ensure both safe and efficient storage and transportation systems. Another primary concern is environmental impact, as the development of hydrogen infrastructure must align with sustainability goals by minimizing emissions and reducing ecological harm [49]. Furthermore, regulatory compliance issues were highlighted, particularly inconsistencies between state and federal regulations, which pose significant barriers to effective coordination and implementation of hydrogen projects.

To overcome these challenges and accelerate the transition to a low-carbon economy, policymakers should prioritize the development of advanced energy storage solutions, the reinforcement of grid infrastructure, and the expansion of electric vehicle charging networks [50]. Implementing innovative solutions can help Australia bridge regulatory gaps and improve operational integrity in the hydrogen sector. For example, using blockchain technology in industry documentation can enhance safety, accountability, and information security, supporting sustainability efforts and strengthening Australia's global hydrogen market position. Blockchain's decentralized and tamper-proof architecture enables transparent tracking of hydrogen across production, transportation and storage stages. By providing an immutable record of actions and enabling precise identification of responsible individuals, blockchain technology supports regulatory compliance, minimizes risks and strengthens trust among stakeholders [51,52]. This approach could complement harmonization efforts by establishing standardized, auditable systems adaptable to diverse jurisdictional frameworks. Clear and consistent regulations enable stakeholders to navigate the technical complexities of hydrogen transportation across various modes, such as pipelines, road, rail and maritime, while identifying and addressing specific regulatory gaps [52].

The analysis also revealed other challenges that impede the hydrogen economy's progress:

1. Regulatory gaps are a significant obstacle, with states adopting hydrogen standards unevenly, leading to fragmentation and inefficiencies [2,4,33]. Regulatory fragmentation is a global challenge, noting disparities in hydrogen standards across the EU, U.S. and Asia [3,7,51].
2. Infrastructure development opportunities exist for expanding hydrogen transport and storage facilities, which will enhance supply chain functionality as the market matures [50].
3. Cost barriers remain a critical issue, as the development and maintenance of hydrogen logistics and storage systems require significant financial resources, which can hinder widespread adoption [45,53].

4.3.1. Unified Hydrogen Policy for Australia: Enhancing Global Competitiveness

Australia possesses several key advantages in developing a hydrogen energy economy compared to countries such as the USA, China, Norway, UAE, Qatar, and Chile. Firstly, the country is rich in natural resources, including abundant reserves of natural gas, as well as vast potential for wind and solar energy. This wealth of renewable resources provides a strong foundation for both green and blue hydrogen production. Additionally, as the twelfth-largest economy in the world, Australia has the economic capacity to scale hydrogen projects and attract significant global investment. Its geographic location is also advantageous, offering close access to major hydrogen importers in Asia, such as Japan and South Korea, as well as European markets, which reduces export logistics costs [51]. Australia's strong national hydrogen strategy, stable trade environment, and advanced research ecosystem position it as a global hydrogen leader. To fully apply these strengths, a unified national policy is needed to boost international competitiveness and promote collaboration across states and territories in advancing green hydrogen technologies.

A national hydrogen strategy should serve as the cornerstone of this effort, focusing on coordinated investments in hydrogen production, storage and export infrastructure to avoid duplication and inefficiencies. Strengthening partnerships with key trading nations, such as Japan, South Korea and Germany, is crucial for developing hydrogen export corridors, which will solidify Australia's position as a leading supplier in the global hydrogen market [51]. Establishing a centralized national hydrogen investment fund to pool resources and allocate funding based on project merit and alignment with national priorities is essential for streamlining support for projects that advance Australia's hydrogen industry, particularly those with export potential [53–55]. Furthermore, integrating robust risk mitigation measures into hydrogen transport, storage and handling regulations will enhance the safety and reliability of the hydrogen supply chain, reinforcing both domestic and international confidence in Australian hydrogen [55]. By adopting this unified strategy, Australia's geographic advantages, combined with its investment in infrastructure and renewable energy resources, position it favorably to reduce export costs for hydrogen, making it an attractive option for international buyers [56].

4.3.2. Alignment of State-Level Initiatives with Australia's National Hydrogen Strategy

Effective state-level hydrogen initiatives must align with Australia's broader national hydrogen strategy, using each region's distinct strengths while adhering to international

ISO standards [36,38,40,41]. QLD and WA lead in hydrogen export development, with their coastal infrastructure and proximity to Asia-Pacific markets ensuring compliance with ISO 14687 (hydrogen quality) [36] and ISO 19880 (fueling stations) [38], as shown in Figure 2. The figure integrates state-level ISO alignment from Table 2 alongside regional capabilities: QLD and WA prioritize liquefaction and port readiness; TAS and SA leverage renewable resources for green hydrogen production, though partial alignment with ISO 16111 (storage) [39] necessitates infrastructure upgrades. VIC and NSW focus on urban integration, aligning with ISO 22734 (Hydrogen generators using water electrolysis) [41], while the NT advances solar-powered projects with traceability gaps addressed via blockchain frameworks. These regional strategies collectively support national goals while identifying priority areas for ISO harmonization [57,58].

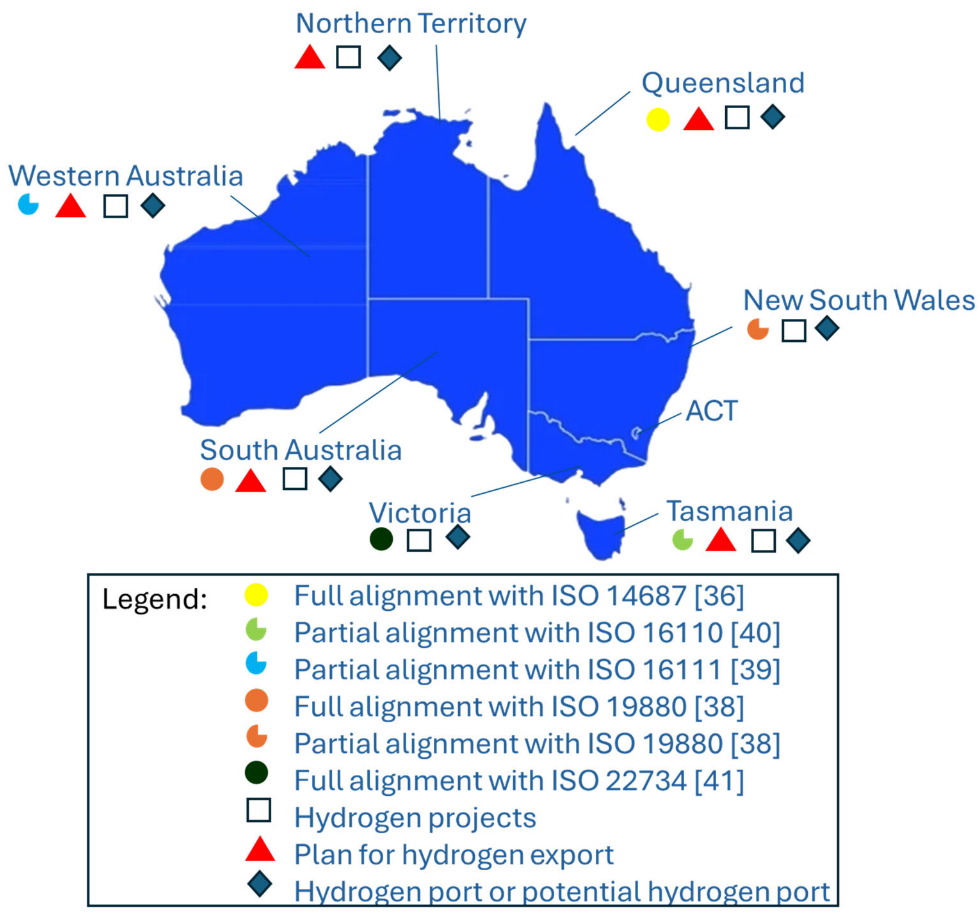

Figure 2. An overview of Australia's Hydrogen Landscape.

NSW is focusing on developing hydrogen hubs and enhancing interstate collaboration through better transportation infrastructure [34]. VIC, with its urban characteristics, is prioritizing the expansion of hydrogen-powered public transportation and integrating urban applications into the broader national supply chain [16]. QLD, given its geographical advantage, balances large-scale exportable hydrogen production with domestic application [35]. Furthermore, except for the ACT, all states either possess existing hydrogen port infrastructure or have the potential to develop it [59]. This coordinated, region-specific approach will strengthen Australia's export capabilities and ensure a comprehensive framework for domestic deployment, positioning the nation as a formidable player in the global hydrogen economy.

SA can lead in hydrogen legislation by advancing seasonal storage for energy security and export reliability. WA should coordinate shared infrastructure to boost export efficiency.

TAS, with its hydroelectricity, is export-ready and can supply freshwater, and quality infrastructure [24]. NT should focus on solar-powered hydrogen for remote areas and inclusive Indigenous participation [25,26]. ACT can pursue niche uses like fleet vehicles and backup systems, positioning itself as a policy innovation hub.

4.3.3. Key Strategies to Minimize Internal Competition

To mitigate internal competition among Australian states and territories, a coordinated national strategy must prioritize collaboration and resource efficiency [5,6]. Strategic project allocation should align regional capabilities with overarching goals—for example, directing WA toward export-oriented hydrogen production while using TAS's renewable energy potential for green hydrogen generation. Globally, regions with abundant low-cost renewables, space for solar or wind infrastructure, water access and proximity to demand centers are poised to emerge as hydrogen production hubs, reshaping geoeconomic dynamics. Australia's renewable-rich regions, including its sun-drenched interior and wind-prone coastlines, could position the nation as a key player in this transition.

However, the hydrogen sector's economic viability differs fundamentally from traditional fossil fuels. Declining costs for green hydrogen will further intensify competition, inviting diverse market entrants and compressing profit margins [55,60]. To address these challenges, Australia must pursue joint infrastructure investments, such as shared export terminals and refueling networks, to eliminate redundant spending. A federal hydrogen collaboration body could institutionalize cooperation, ensuring equitable benefit-sharing, conflict resolution and alignment of cross-state initiatives. This governance model would reinforce Australia's capacity to harness regional strengths while advancing a unified, globally competitive hydrogen economy.

4.3.4. Enhancing International Competitiveness

A unified national approach is vital to streamline Australia's hydrogen policies, reduce inefficiencies and attract international investment. By presenting a cohesive front, Australia can establish itself as a reliable supplier of high-quality hydrogen, enhancing its reputation on the global stage. Coordination among states will strengthen domestic capabilities and position Australia as a leader in the emerging hydrogen economy, driving sustainable growth and fostering global partnerships.

This study proposes the following policy measures:

1. Unified Hydrogen Framework:
    a. Establish a national regulatory structure to harmonize standards across states.
    b. Ensure adherence to ISO standards, notably:
        i. ISO 14687 [36] for hydrogen quality.
        ii. ISO 19880 [38] for hydrogen fueling infrastructure.
2. Infrastructure Development:
    a. Create a coordinated national blueprint for hydrogen production hubs, storage facilities and transport corridors.
    b. Reduce duplication and ensure strategic alignment with export priorities.
3. National Hydrogen Certification Scheme:
    a. Develop a certification scheme aligned with international standards.
    b. Facilitate seamless interstate trade and enhance Australia's global reputation.
4. Collaborative Governance through establishing a federal hydrogen collaboration body to:
    a. Coordinate efforts among states and territories.
    b. Oversee regulatory compliance.
    c. Ensure equitable development across the country.

4.3.5. Lessons from the EU and California for Australia's Hydrogen Policy Design

The EU and California serve as exemplary models for advancing hydrogen policy frameworks that Australia can adapt to its unique context. The EU's Regulation 2023/1804 on alternative fuels infrastructure emphasizes harmonized standards across member states, ensuring consistency in hydrogen quality, safety, and fueling infrastructure [61]. This cohesive approach facilitates cross-border trade, reduces compliance costs, and enhances investor confidence. The EU's Regulation 2023/1804 establishes uniform criteria for alternative fuels infrastructure, including hydrogen fueling stations, mandating adherence to international standards like ISO 14687 for hydrogen quality and ISO 19880 for fueling station safety. By standardizing these requirements across member states, the regulation minimizes regulatory discrepancies, thereby streamlining cross-border trade, lowering compliance costs for businesses, and fostering a stable investment environment for hydrogen infrastructure projects [61].

Similarly, California has emerged as a global leader in hydrogen adoption through ambitious targets, substantial public funding for hydrogen fueling stations, and adherence to international standards such as ISO 19880 [38] for fueling station safety. The state's Hydrogen Highway initiative, supported by public-private partnerships (PPPs) like the California Fuel Cell Partnership, has been instrumental in accelerating hydrogen infrastructure deployment [62]. California has allocated significant funding, such as USD230 million through the Clean Transportation Program, and actively collaborates with stakeholders under PPPs like the California Fuel Cell Partnership to achieve its target of 200 hydrogen fueling stations by 2030 [63].

For Australia, these examples highlight the importance of harmonized state-level policies aligned with national objectives. Implementing a centralized regulatory framework akin to the EU's Regulation 2023/1804 could resolve interstate inconsistencies, while adopting California's funding mechanisms and stakeholder collaboration models could improve the project efficiency of hydrogen infrastructure development. By drawing on these international best practices, Australia can position itself as a global leader in the hydrogen economy, fostering a cohesive, scalable, and sustainable hydrogen framework.

5. Proactive Regulation for Hydrogen Supply (PRHS)

To address the regulatory and operational challenges identified in the hydrogen supply chain, innovative technological solutions are essential for ensuring efficiency, safety, and compliance. Among these, blockchain technology emerges as a transformative tool, capable of bridging gaps in fragmented regulatory frameworks and enabling seamless integration across jurisdictions. The integration of blockchain technology into the hydrogen energy sector offers a promising solution for enhancing safety, compliance, and scalability, while also addressing international market competition [64]. Hydrogen production, transportation, and storage pose unique challenges necessitating a robust policy framework to improve operational safety and accountability. Blockchain technology significantly enhances hydrogen regulation by ensuring data transparency, traceability, and automation, effectively mitigating fragmented standards across jurisdictions. However, its implementation comes with challenges, including high costs, cybersecurity risks, and energy consumption, which require thorough evaluation. Alternatives such as digital twins, distributed ledger technologies (DLT), and cloud-based systems provide scalable and cost-effective options. A hybrid approach, combining blockchain for traceability with other technologies for operational efficiency, offers a balanced pathway to innovation and practicality. To maintain simplicity and focus, this paper uses blockchain technology as an illustrative example.

To enhance the PRHS framework, effective governance is crucial and should be approached from an anticipatory perspective. As public policy and the involvement of public safety, adaptability is important in regulatory design. It enables proactive strategies that can evolve in tandem with technological advancements in the hydrogen sector. Furthermore, integrating regulatory sandbox concepts will provide a practical framework for testing innovative solutions, such as blockchain technology, within controlled environments. This approach ensures that new technologies can be safely and effectively evaluated while remaining compliant with existing regulations [65]. By anchoring the PRHS framework in these theoretical foundations, we can more effectively tackle the dynamic challenges of hydrogen supply chains and cultivate a more resilient regulatory environment.

With reference to the scenario of Australia, such a policy framework should cope with the following:

5.1. Safety and Compliance Enhancement

5.1.1. Documentation and Accountability

The hydrogen supply chain involves multiple stages and personnel, making it crucial to document every action taken. Blockchain technology can provide a secure and immutable record of all transactions and actions, ensuring that everyone's responsibilities are clearly defined and traceable [66]. This transparency is vital for safety, as it allows for quick identification of accountability in the event of an incident [67].

5.1.2. Immutable Records

By utilizing blockchain, all data related to hydrogen handling, from production to distribution, can be hashed and stored in a manner that prevents tampering [66,67]. This feature is essential for maintaining compliance with safety regulations and standards such as ISO 14687 [36] and ISO 19880 [38]. Any unauthorized changes to the data would be easily detectable, reinforcing the integrity of safety protocols.

5.1.3. Enhancing Safety Protocols for Hydrogen Storage and Transportation

To address the safety challenges associated with hydrogen's flammability and storage risks, advanced monitoring systems, including IoT-enabled sensors and blockchain-based platforms, can be deployed to track hydrogen conditions in real time. The use of hydrogen-compatible materials, such as stainless steel and carbon fiber composites, ensures long-term system integrity. Emergency response frameworks tailored to hydrogen incidents, public awareness campaigns, and harmonized safety standards (e.g., ISO 19880 [38] and 16111 [39]) may further enhance safety. These measures can align with the PRHS framework through emphasizing anticipatory governance and risk mitigation across storage and transportation stages.

5.2. Scalability and Efficiency

5.2.1. Streamlined Processes

The use of blockchain can facilitate more efficient logistics in hydrogen transportation and storage. By providing a decentralized ledger that all stakeholders can access, it reduces the need for intermediaries and minimizes delays in the supply chain [64]. This efficiency is particularly beneficial for regions with limited infrastructure, such as NT and TAS, where high costs and geographic constraints pose significant challenges.

5.2.2. Cost Reduction and Revenue Opportunities

The implementation of blockchain technology can significantly reduce costs by minimizing administrative overhead and improving operational efficiency across Australia's hydrogen supply chain [67]. This is particularly valuable in addressing regulatory inconsistencies between states with varying compliance requirements. For example, blockchain-enabled smart contracts could automatically validate hydrogen quality standards during interstate transport, eliminating the costly adjustments currently required when moving hydrogen from QLD (which adheres to ISO 14687) to states with different requirements like TAS or NT.

These blockchain-driven efficiencies generate substantial cost savings that can be strategically reinvested into infrastructure development and technological innovation, accelerating the growth of Australia's hydrogen economy. The technology also reduces compliance costs by creating immutable records that satisfy multiple jurisdictional requirements through a single standardized process, eliminating duplicative documentation and quality control recalibrations.

During the early implementation stages, revenue generation may be supported through PPPs [68] and targeted levies [69]. Such funding approaches have demonstrated success in the transport sectors of Hong Kong, Europe, and China [70,71], indicating their potential applicability to Australia's hydrogen infrastructure development. By combining blockchain's efficiency benefits with strategic funding mechanisms, Australia can overcome regulatory fragmentation while building a more competitive and cost-effective hydrogen economy.

5.3. International Market Competitiveness

5.3.1. Standardization and Certification

A unified approach to hydrogen regulation, supported by blockchain technology, can help Australia align more closely with international standards [72,73]. By ensuring compliance with ISO standards and creating a national hydrogen certification scheme, Australia can enhance its reputation as a reliable supplier of high-quality hydrogen. This alignment is crucial for attracting international investment and fostering global partnerships.

5.3.2. Enhanced Security

The cryptographic nature of blockchain technology ensures that all transactions are secure and verifiable [74]. This security is essential for building trust with international partners and consumers, particularly in a market where safety and quality are paramount.

5.4. PRHS Framework Architecture

Incorporating blockchain technology into the hydrogen energy sector can significantly enhance safety, compliance and operational efficiency. PRHS is designed and illustrated in Figure 3 [75]. The application of blockchain enhances the hydrogen energy supply chain by enabling real-time tracking, automated certification, secure trading, and transparent emissions data. Integrating blockchain into the hydrogen supply chain enhanced transparency through immutable records of hydrogen origin, emissions, and logistics. It enables automation via smart contracts for trade, certification, and compliance, improving efficiency by reducing transaction costs and intermediaries. It also supports market integration through cross-border compatibility with global certification systems and boosts investor confidence by providing verifiable sustainability and performance data.

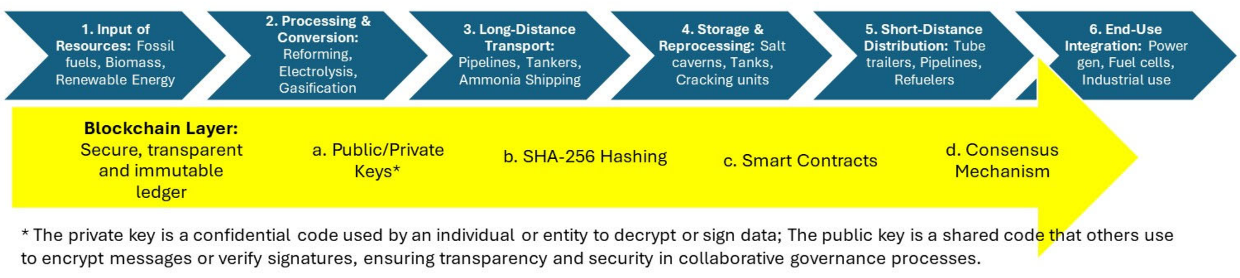

Figure 3. PRHS: A Blockchain based regulatory framework.

PRHS captured data flows, stored and analyzed information across the key stages of hydrogen logistics:

1. Input of Resources: Data from the sourcing of raw materials such as fossil fuels, biomass and renewable energy is securely recorded using blockchain. Each data entry is digitally signed by the user's private key, ensuring authenticity and accountability. The public key allows other stakeholders to verify the data without exposing sensitive information, ensuring trust across the supply chain.
2. Processing & Conversion: Blockchain tracks the entire transformation process, from steam methane reforming to electrolysis and chemical carrier synthesis. Each process step generates hashed data records using algorithms like SHA-256. The immutability of these records prevents unauthorized alterations, ensuring compliance with safety standards and emission controls.
3. Long-Distance Transport: Hydrogen logistics data, such as transit conditions, storage parameters and transport routes (e.g., pipelines, cryogenic tankers, or liquid organic hydrogen carriers), is hashed and stored in blocks. Each block is cryptographically linked to the previous one, creating a verifiable chain. Any tampering with transport data would produce mismatched hash values, immediately flagging anomalies.
4. Storage & Reprocessing: Data from storage systems (e.g., underground salt caverns, pressurized tanks, or ammonia cracking units) is recorded in real time. The use of digital signatures ensures that data originates from authorized devices, while hashing guarantees data integrity. Blockchain also enables predictive maintenance by securely analyzing sensor data for anomalies.
5. Short-Distance Distribution: Localized delivery methods, including tube trailers, gaseous pipelines and mobile refuelers, are monitored through blockchain-enabled devices. Data collected during distribution is hashed and added to the blockchain, forming a reliable, tamper-proof record of the hydrogen's journey to its destination.
6. End-Use Integration: Blockchain verifies hydrogen's final use in industrial refining, power generation, fuel cell vehicles and heating networks. The immutable nature of blockchain data ensures accurate carbon accounting, enabling stakeholders to trace the energy source and its environmental impact.

The Role of Public and Private Keys: Each participant in the hydrogen supply chain is assigned a unique pair of keys: a public key for verification and a private key for generating digital signatures. For example, when a logistics contractor uploads data to the blockchain, they sign the data using their private key. This signature ensures that the data is authentic and cannot be repudiated. Other participants can verify the data's integrity using the contractor's public key.

Hashing for Data Security: All data stored in the blockchain is hashed using the SHA-256 algorithm. This process converts input data into a fixed-length cryptographic hash, making it almost impossible to reverse-engineer the original data. Even a minor modification to the input data produces a completely different hash value, making tampering detectable. For example, if a transport record is altered to conceal a delay, the hash of that record will no longer match the hash stored in the subsequent block, immediately exposing the tampering attempt.

Blockchain Creation Process: The creation of each new block in the hydrogen logistics framework follows a structured process:

User 1 hashes the plain text data "(A)" using SHA-256 hashing algorithm, generating a hashed value (H_1 = hash(A)), then encrypt the hashed value with his own private key ($Sign_{user1}(H_1)$). The initial Block (Block "(1)") contains the plaintext data "(A)" and the digitally signed value ($Sign_{user1}(H_1)$).

For subsequent blocks, such as (Block "(2)"), the hash value is generated by hashing the plain text data "(B)" together with the value of pervious Block (H_2 = hash(data "(B)" + Block "(1)"), this result is then signed by User 2 ($Sign_{user2}(H_2)$). This Block (Block "(2)") contains the plaintext data "(B)" and the digitally signed value ($Sign_{user2}(H_2)$).

This process continues, linking each block cryptographically to the previous one, forming an immutable and transparent chain.

Benefits for Hydrogen Logistics

By applying blockchain technology, the hydrogen logistics framework ensures that:

1. Accountability: Every transaction or data entry is attributable to a specific user or device, follows to respective digital signatures [43].
2. Transparency: Immutable records on the blockchain provide verifiable evidence of compliance with ISO standards and operational protocols [67].
3. Security: Hashing safeguards data integrity, while the decentralized nature of blockchain ensures that every participant maintains an identical copy of the ledger, making tampering nearly impossible [74].
4. Legal Utility: The immutable and transparent nature of blockchain data provides compelling evidence for legal and regulatory purposes, enabling the identification of individuals responsible for specific actions [75].

For instance, in a scenario involving a logistics contractor using blockchain-enabled monitoring devices, the data collected (e.g., temperature, pressure and transit times) is hashed and uploaded to a decentralized storage system. Smart contracts automatically enforce compliance with relevant ISO standards. Any deviation from expected parameters triggers alerts, enabling immediate corrective action. Blockchain providers analyze the aggregated data to generate real-time insights, enhancing decision-making and operational efficiency.

By incorporating these blockchain concepts, the hydrogen logistics framework ensures robust data security and traceability and establishes a reliable foundation for the hydrogen economy's sustainable growth. The expected benefits are summarized in Table 3. The hydrogen logistics framework ensures robust accountability, transparency, and security. Every transaction or data entry is attributable to a specific user or device using digital signatures, which ensures traceability and prevents unauthorized actions. Immutable records on the blockchain provide verifiable evidence of compliance with ISO standards and operational protocols, enhancing transparency across the supply chain. To ensure long-term data integrity and quantum resistance, the framework replaces traditional SHA-256 hashing with post-quantum cryptographic algorithms such as SHA-3 (Keccak) combined with hash-based signatures (e.g., SPHINCS+). These mechanisms generate tamper-proof cryptographic hashes while mitigating vulnerabilities to Shor's and Grover's quantum algorithms, which could otherwise compromise classical hash functions. For encryption, lattice-based protocols (e.g., CRYSTALS-Kyber) are implemented to safeguard sensitive hydrogen supply chain data against quantum decryption attacks. This dual-layered approach, quantum-resistant hashing and encryption, ensures compliance with evolving regulatory standards (e.g., NIST Post-Quantum Cryptography Project) and future-proofs the traceability system against emerging quantum threats. [76]. Furthermore, the immutable and transparent nature of blockchain data serves as compelling evidence for legal and regulatory purposes, enabling the identification of responsible parties in the event of disputes or safety incidents. By integrating these features, the framework addresses key challenges in managing hydrogen logistics while fostering operational trust and efficiency.

Table 3. Blockchain Benefits by Supply Chain Stage.

Stage	Blockchain Benefit	ISO Standards Alignment
Input of Resources	Verifiable renewable source data	ISO 16110 [40]
Processing & Conversion	Tamper-proof records of electrolysis methods	ISO 22734 [41]
Long-Distance Transport	Secure tracking of transit conditions	ISO 19880 [38]
Storage & Reprocessing	Carbon emission records validation at end-use integration	ISO 16111 [39]
Short-Distance Distribution	Transparent delivery logs	ISO 19880 [38]
End-Use Integration	Emissions validation and carbon accounting	ISO 14687 [36]

The PRHS framework (Figure 4) integrates advanced technologies, such as blockchain and public-private key infrastructure, to ensure robust data security, integrity, and regulatory compliance across the hydrogen supply chain [67]. Its six-stage information flow architecture (Figure 3) facilitates real-time monitoring, auditing, and automated verification through smart contracts, aligning seamlessly with ISO standards, including ISO 14687 (hydrogen quality) and ISO 19880 (fueling infrastructure) [36,38,51,74].

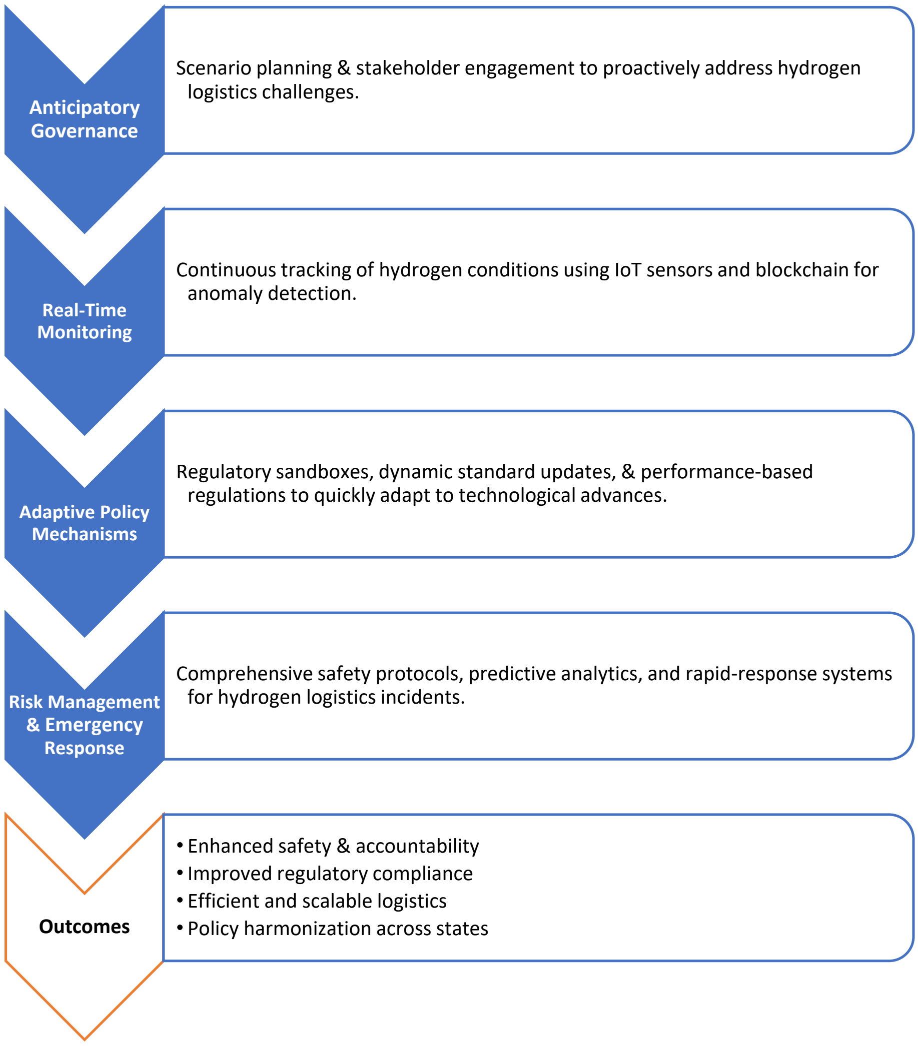

Figure 4. PRHS framework.

Beyond technical advancements, the PRHS framework incorporates social impact considerations by addressing energy justice, fostering stakeholder engagement, and anticipating technological implications. Blockchain technology enhances transparency and accountability, building public trust and promoting inclusivity. Additionally, PRHS supports sustainable regional development, mitigates risks such as community displacement, and aligns global sustainability goals. By prioritizing local community benefits and equitable transitions, PRHS ensures that hydrogen development contributes to a just and inclusive energy future [77].

The Murchison Green Hydrogen Project, funded with AUD$814 million under Australia's Hydrogen Headstart Program [78], may exemplify the application of PRHS. The project combines 1.5 GW of electrolysis capacity, 1.2 GW of solar PV, 1.7 GW of wind energy, a 600 MW battery, and desalination to produce renewable hydrogen and ammonia off-grid in WA. Using PRHS principles, blockchain creates immutable records for tracking renewable energy sourcing, water sustainability, and regulatory compliance, ensuring transparency and trust. Predictive maintenance systems enhance operational reliability, facilitating efficient large-scale production [67,74]. By linking PRHS to such projects, Australia will promote scalable, export-ready hydrogen infrastructure and strengthens its leadership in global decarbonization through standardized, auditable frameworks supporting industries like steelmaking, agriculture, and transportation.

6. Conclusions

The rapid expansion of Australia's hydrogen economy stresses the critical need for a cohesive and adaptive regulatory framework to address the unique challenges of hydrogen transportation and storage. This study highlights the importance of harmonizing fragmented state and federal policies, adopting international standards and applying innovative technologies such as blockchain to enhance safety, regulatory compliance, and operational efficiency. By proactively aligning regulatory frameworks with technological advancements, Australia can overcome barriers related to high investment cost, safety risks, infrastructure gaps, and regulatory inconsistencies, as illustrated in Table 4.

Table 4. Australian hydrogen energy development: Policy recommendations.

Strategic Action	Objective
National hydrogen regulatory framework	Harmonizing state regulations with international benchmarks
Infrastructure Investment Plan by PPP	Avoiding investment duplication, e.g., sharing export facilities
Developing Certification Scheme	Building public trust and traceability via blockchain system

The proposed PRHS framework emphasizes anticipatory governance, real-time monitoring, and immutable data records, providing a robust approach to addressing challenges in safety, regulatory compliance, and international competitiveness. The integration of blockchain technology into the hydrogen supply chain further enhances transparency, accountability, and trust, fostering greater collaboration among stakeholders.

To advance the application of blockchain technology in the hydrogen sector, future research could investigate empirical cases, such as Australia's Hydrogen Centre program, to assess its feasibility and effectiveness in real-world scenarios. Such studies would offer valuable insights into how blockchain can improve safety, traceability, and operational efficiency across hydrogen supply chains. Furthermore, employing methods such as content analysis and stakeholder interviews could provide deeper insights into the challenges and opportunities associated with implementing blockchain solutions, while offering practical perspectives for refining these technologies.

In addition to addressing regulatory and operational challenges, the PRHS framework integrates social impact considerations, enabling policymakers to systematically address the societal implications of hydrogen supply chains. This approach facilitates sustainable and equitable energy transitions, ensuring that hydrogen development aligns with broader societal and environmental goals [79]. The framework aligns with the socio-technical transitions framework, which incorporates insights from economics, the sociology of innovation, and neo-institutional theory to address politics and policy analysis. Organizations such as Forum for the Future and WWF may apply multi-level perspective to guide sustainability strategies and assess transitions, such as low-carbon pathways. The PRHS framework offers a robust tool for understanding long-term transformative changes in systems like energy and transport [80].

As the global need for clean energy continues to grow, Australia's wealth of renewable resources, strategic geographical positioning, and thriving research environment provide a strong foundation for leading the way in the hydrogen economy. The transition to hydrogen as a clean energy source, replacing fossil fuels, is vital for fostering sustainable transportation and regional development, particularly in areas with high energy costs that aim to prioritize renewable resources [69]. Australia's progress is strengthened by comprehensive strategies across jurisdictions, such as the 2024 National Hydrogen Strategy [5] and state-level initiatives like QLD's Hydrogen Industry Strategy 2019–2024 [35] and SA's Hydrogen Action Plan 2019 [29]. These coordinated efforts, as detailed on the HyResource platform by CSIRO, are critical for establishing a unified national approach and positioning Australia as a global leader in the hydrogen economy [81].

While the PRHS framework offers a robust tool for managing regulatory, operational, and societal challenges in hydrogen supply chains, further research is needed to explore the integration of adaptive governance methods. Incorporating elements such as leadership promotion and cross-scale coordination could enhance the framework's capacity to address the societal and environmental dimensions of hydrogen transitions. Future studies could evaluate how these methods can be operationalized within diverse socio-technical and geopolitical contexts to facilitate equitable and sustainable energy systems [82].

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Abbreviations

The following abbreviations are used in this manuscript:

NSW	New South Wales
VIC	Victoria
QLD	Queensland
SA	South Australia
WA	Western Australia
TAS	Tasmania
ACT	Australian Capital Territory
NT	Northern Territory
PRHS	Proactive Regulation for Hydrogen Supply

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