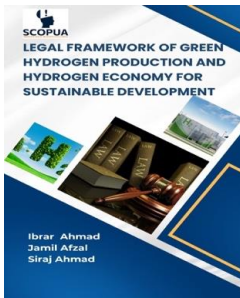


CHAPTER SEVEN

LEGAL FRAMEWORK FOR HYDROGEN ECONOMY AND FUTURE DIRECTIONS OF GLOBAL GREEN HYDROGEN ECONOMY

IBRAR AHMAD ¹, JAMIL AFZAL ^{2*} AND
SIRAJ AHMAD ³

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¹Southwest university of political science and Law, China

²International Islamic University, Malaysia

³Tianjin University, Tianjin, China

*Corresponding: sirjamilafzal@gmail.com (Afzal, J.)

Abstract

The emergence of the global green hydrogen economy presents a complex legal challenge, necessitating the development of flexible and holistic legal frameworks to support new technologies within distinct sectors and across various legal systems. From fledgling novelties to indispensable elements of energy systems worldwide, hydrogen technologies are poised to transform, and legal frameworks will play a crucial role in navigating a complex regulatory landscape to drive investment, ensure safety and support a sustainable presence. The complexity of hydrogen production, transport, storage, and use needs consistent regulation to facilitate smooth integration into the industrial, transport, and energy sectors. So this chapter focuses on a common legal framework for the hydrogen economy and future directions for the global green hydrogen economy.

Keywords: *Future Legal Direction of Hydrogen Economy; Global Green Hydrogen Economy; International Law; Legal Framework of the Hydrogen Economy*

7.1. Introduction

Legal certainty is a key factor in the creation of confidence and stability for investors and markets [1]. Lack of transparent, stable, and consistent regulation creates an increased level of uncertainty for stakeholders, which can act as a barrier to the heavy capital investment involved in the scale-up of hydrogen infrastructure [2]. Through legal support from the Green Hydrogen Legal Capacity Unit (GH2L, 2024), it is clear that clear administrative frameworks, licensing regimes, and enforcement systems should be put in place that set out the rights and responsibilities of all players in the hydrogen chain. These systems must also include elements, such as guarantees of origin, to verify hydrogen's renewability and ensure the integrity of the market and the environmental outcomes. Intercontinental cooperation and harmonisation of regulations are still important issues in this context. The hydrogen chain involves several jurisdictions, often with different legal traditions, regulatory priorities, and institutional capabilities. As the German TransHyDE study



suggests, despite promising legislation initiatives, legal fragmentation already at the national and EU level is posing problems in accelerating the scale of hydrogen projects [3]. There is also fragmentation globally, with no common format or harmonised cross-border regulation, further complicating the issue of developing hydrogen infrastructure and trade. The large number of regulators, overlapping mandates, and differing safety and environmental standards require close and common approaches to policy development and cooperation between countries.

Regulatory frameworks play a role in facilitating the shift from conventional fossil-fuel to renewable hydrogen-based energy systems. They will serve as the basis for the incorporation of hydrogen technologies into natural energy markets, the accommodation of grid operation requirements, and environmental and public health considerations. For example, in Spain, Royal Decree-Law 6/2022 incorporates the supply of green hydrogen into the established natural gas regulatory frameworks, but with specific rules for hydrogen network operators, showing adaptive legal innovation [4],[5]. In the United States, a patchwork of complex regulations, which includes both federal and state agencies, regulates hydrogen projects, requiring integrated policies for effective government action to promote them, for example, the Hydrogen Interagency Task Force to rationalise regulation (Clean Air Task Force, 2025). As of mid-2025, in the European Union alone, there are more than 750 hydrogen projects in the pipeline, bolstered by regulatory frameworks targeting 40 GW of electrolyser capacity deployments by 2030 (European Clean Hydrogen Alliance, 2024). Nationally, governments are adopting policies to solicit investment, establish safety criteria, and encourage market growth around the world. But such efforts are still in their infancy and unevenly implemented, highlighting the pressing need for robust, flexible, and consistent legal standards capable of absorbing

technological change, market developments, and environmental imperatives.

7.2. Common Legal Framework for Hydrogen Economy

A model legal framework for the hydrogen economy is a collection of legal principles and instruments that are meant to provide general standards for laws and regulations across legal systems for the purpose of effective governance of hydrogen production, transportation, storage, and trading. What such a system does is to put in place the same set of rules to which everyone in the hydrogen value chain, from producers and distributors to users and regulators, is accountable for their rights, obligations, and liabilities. It is needed to avoid legal uncertainty, support cross-border collaboration, and ensure that hydrogen technologies can be scaled up under the same safety, environmental, and commercial requirements. Due to the variety of hydrogen production (green, blue, grey hydrogen), transportation (through pipelines or in liquefied hydrogen carriers), and end-use applications in various sectors (industry, transport, power), legal consistency is required [6],[7]. A shared legal framework facilitates market integration through predictable regulatory conditions that encourage investment, reduce risks, and stimulate innovation. It also encourages the establishment of reliable certification systems, like guarantees of origin, that are essential to verify the renewable nature of hydrogen and thus to instil confidence among consumers and investors across the globe [8].

Companies have also adopted different certification and sustainability standards, and there is no agreed framework by which to verify “green” hydrogen production. This discrepancy adds to the complexity of cross-border business and can lead to a fragmented market. In addition, the administrative regime for the licensing of hydrogen production and distribution is often



rudimentary or inconsistent, stifling project deployment. These deficiencies highlight the pressing need for basic legal frameworks designed to clarify jurisdictions, to delineate licensing regimes, and to converge safety and environmental regulations, but not yet for concrete policy measures and enforcement. International agreements and organisations find value in establishing a foundation for collaboration and convergence in terms of hydrogen governance. Initiatives such as the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), the International Renewable Energy Agency (IRENA), and the European Union (EU) have led the way in establishing common standards and dialogues between nations. Such organisations concentrate on defined terms, safety rules and certification specifications that provide the underpinning for both the legal and technical framework for homologation. The umbrella goal of a shared legal framework is to enable the hydrogen economy to flourish on a global scale through better regulatory alignment and coordination. Joint legal principles and administrative solutions can help to reduce fragmentation, increase interoperability, and provide a clear, stable environment for innovation and investment. This baseline legal edifice provides the platform for specific policy actions, financing mechanisms, trading laws, and safety standards, as will be illustrated in the next section on recommendations. Only with such a sound legal basis can the hydrogen economy become more than a patchwork of pilot projects and grow into a fully integrated market.

7.2.1. Intellectual Property Law and the Hydrogen Economy

Intellectual property (IP) is essential in the development of the emerging hydrogen economy by protecting the innovations that are vital for hydrogen production, fuel cell designs, storage concepts, and accompanying infrastructure [9],[10]. With a rapidly changing hydrogen market, it is important to protect proprietary

technology so that inventors and companies may realize competitive advantage, secure investment, and encourage further R&D. The interdisciplinary nature of the hydrogen economy in areas from chemistry, materials science, and engineering to renewable energy, creating demand for strong IP frameworks to navigate complicated innovations and enable technology commercialization worldwide [11],[12]. Patent law plays a vital role in promoting innovation in the hydrogen economy by giving inventors exclusive rights to new inventions, usually for 20 years in return for public disclosure. In hydrogen technologies, patentable improvements may encompass, for example, advanced methods of hydrogen production (e.g., electrolysis), novel catalysts, hydrogen storage media (e.g., metal hydrides, compressed gas tanks), and fuel-cell technology designs that enhance efficiency and longevity (World Economic Forum, 2023). Patents safeguard the novel ideas and technical advances that distinguish new hydrogen technologies from the prior art, and help companies recoup their R&D investment and establish themselves as market leaders. Recent trends underline the importance of patents: Europe and Japan are the top global patent filers in hydrogen technologies, responsible for 28% and 24% of international patent families between 2011 and 2020, with a marked increase in low-emission production processes (EPO & IEA, 2023). This filing activity is indicative of the strategic value of defending innovation related to climate objectives and energy transition needs. Technology transfer and patent licensing are powerful tools to deploy hydrogen technologies on a global scale. Licensing is a mechanism that allows patentees to license other parties to use the technology, thus promoting collaboration between companies, regions, and countries. Such a collaboration structure facilitates speeding the commercialisation of hydrogen infrastructure through providing access to proprietary technologies on terms that do not carry the need for an outright transfer of ownership. Cross-border license agreements are seen to be



especially crucial in the hydrogen field, where infrastructure projects are cross-jurisdictional and with different techno-economics. He therefore sees IP rights as a cornerstone for international collaboration, joint ventures, and consortia that combine knowledge and resources to resolve technical and financial hurdles. The management of IP portfolios plays an important role with regard to knowledge transfer, and at the same time, attention is being paid to the maintenance of commercial incentives to create a dynamic environment favourable to the invention and implementation.

However, IP protection in the hydrogen economy brings certain challenges as well. One major issue is the development of patent thickets in which overlapping patents by different firms lead to complex licensing environments that have the potential to suppress commercialisation and the rise of transaction costs. This thicket can be negotiated via careful IP strategy and negotiation of cross-licensing agreements. The lack of harmonised patent laws and enforcement mechanisms across the world also poses challenges and complicates global IP protection. Differences in patentability standards, levels of examination, and enforcement can result in uneven playing fields across jurisdictions, which erodes the ability to predict or rely upon for investment. Furthermore, IP conflicts, such as lawsuits over basic hydrogen technologies, risk impeding innovation and discouraging startups, as well as small and medium-sized companies with limited resources to contest long-term legal disputes. This could imply exacerbating incumbent firms' market power and stifling the spread of disruptive technologies. International collaboration is crucial to solving the jurisdictional IP issues and creating a unified legal landscape for hydrogen research and development. International Bodies such as WIPO and multilateral treaties, including PCT, help standardise application processes and disseminate best IP management practices. At the global level, political attention is needed to support

the convergence of patent examination standards and capacity building, thus increasing the number of players in hydrogen innovation in developing countries. Harmonised IP frameworks break down barriers to technology transfer and licensing, to promote international cooperation that is critical for the expansion of a hydrogen economy.

7.2.2. International Trade Law and the Hydrogen Economy

International trade law regulates the norms and institutions that enable goods and services to legally cross borders with the expectation of a predictable and fair market [13],[14]. Transposing these scenarios to the hydrogen economy, however, harmonised international trade laws will be crucial to facilitate the efficient and secure transfer of hydrogen products, such as green hydrogen and hydrogen-based fuels, between countries. Since hydrogen is becoming an energy carrier with a worldwide market, harmonised trade policy plays an important role in reducing market access barriers and transaction costs and in facilitating investment, leading to market development and integration (WTO & IRENA, 2023). Trade policies and practices are central to this trend: trade agreements set tariff profiles, import/export protocols, and compliance stipulations that will determine the viability and the level playing field for the trade in hydrogen. Failure to achieve such harmonisation would leave space for countries to put up protectionist barriers or create regulatory divergences that divide markets and slow the scaling-up of hydrogen value chains.

However, the worldwide hydrogen market is also threatened by a number of trade-related obstacles embedded in international regulations. One of the key issues remains the imposition of tariffs and duties on hydrogen and related equipment, pushing up costs and deterring international trade. Although several countries have begun reducing tariffs on electrolyzers and hydrogen products, widely varying regimes remain in place around the world,



creating a variety of supply chain economics concerns. But besides tariffs, there are also non-tariff barriers, like import/export quotas, divergent safety standards, and licensing requirements. For instance, the lack of a common definition for “green” hydrogen results in regulatory fragmentation and hinders market entry and consumer confidence. And, not least, while nations have their own rules, not least Europe’s very tight certification and sustainability criteria against fledgling frameworks in, for example, the United States, the Middle East, and some parts of Asia, it all hobbles the market expansion of hydrogen and fetters fluid trading. These issues that are related to trade are some of the barriers to the global development of the hydrogen market.

Global trade agreements serve as the legal framework to remove these impediments, to give synergy to the hydrogen trade. At the same time, the Rules underpinning good trade practices that are written across tariffs, subsidies, and non-discrimination were established in the WTO. Regional trade agreements, including the EU-Mercosur agreement and bilateral agreements, are increasingly including hydrogen trade-relevant provisions that drive regulatory coherence and cooperation. These agreements, by promoting transparency, lowering trade-distorting subsidies, and supporting the mutual recognition of certificates, enable the harmonisation of hydrogen-related regulations. They do not offer set guidelines but do create a secure legal foundation for countries to develop and implement hydrogen trading under agreed rules (WTO & IRENA, 2023). The compatibility with international trade law is key for the expansion and integration of the hydrogen economy. Standardised trade rules, based on international standards and agreements, reduce trade barriers and build confidence in the market, with hydrogen becoming a globally traded commodity. In order to make the most out of the trade of hydrogen in terms of economic and environmental benefits towards addressing tariff and non-tariff

barriers, promoting regulatory alignment, and integrating environmental concerns into trade frameworks are important.

7.2.3. Financing the Hydrogen Economy: Legal and Regulatory Considerations

Funding hydrogen's new economy is a complex mix of challenges and opportunities, which mirrors the coming-of-age of the sector and the substantial investment it will require [15],[16]. Hydrogen schemes, including manufacturing plants, tanks, or pipelines, were expensive to build and held long-term value. Such projects are often exposed to unknown market conditions and changing regulatory environments, which may dissuade private sector involvement. Therefore, strong legal and regulatory frameworks are essential to ensure a predictable and stable environment that encourages and maintains investments. These frameworks minimise the perceived risk, provide access to various financial markets, and are essential for the economics of hydrogen projects. The creation of stable, clear, and predictable legal regimes is essential to demonstrating to investors commitments to reliability. There are different legislative models across the world to encourage investment in hydrogen, introduced by governments around the world. Tax credits and subsidies (such as production tax credits and accelerated depreciation) generally work to enhance the project's economics by reducing operational costs or offering financial benefits at the outset.

Financial and regulatory structures also impact the financeability landscape by affecting access to markets, pricing mechanisms, and commercialisation paths. Realistic and fair price rules foster a secure and predictable remuneration of hydrogen producers becomes crucial for the bankability of projects. Regulatory action, such as the European Union's Hydrogen and Decarbonised Gas Market Package, can be seen supporting these types of transitions of the hydrogen market through providing price



signals. Furthermore, harmonisation of local and global regulations with climate targets is key to ensure that as we finance, we accomplish sustainable hydrogen production. Establishing these as ‘inline’ requires consideration of sustainability criteria and carbon measurement in the processes of approvals and financial incentives, strengthening the environmental integrity of investments. MDBs and IFIs are especially important in stimulating hydrogen investments in developing economies, where financial markets are less developed. Institutions like the World Bank, the European Investment Bank and a variety of regional development banks provide credits, grants, and technical assistance to help close financing gaps and bolster project preparation. Their participation not only contributes finance but also adds credibility to the venture, which draws in more private investment. MDBs also support blended finance structures, which are a mix of concessional public finance and private investment used to derisk and unlock otherwise commercially unfeasible projects.

7.2.4. Regulatory clarity and consistency

Regulatory certainty and stability are the underpinning legal doctrines that the hydrogen economy needs to progress effectively and to ensure its integration into new markets [17],[18]. Regulatory clarity is the degree to which legal rules and regulations for the production, transport and storage, and trade of hydrogen are transparent, predictable, and unambiguous. It provides an accessible and transparent framework for stakeholders, from investors to developers and regulators, to know their rights, responsibilities, and obligations. Regulatory stability requires that all these requirements be merged and adjusted between jurisdictions to avoid clashes between address fragmentation across the hydrogen market. These two principles enable the smooth, cross-industry integration and efficient operation of hydrogen solutions across sectors and regions. Transparency and predictability in regulation a key factors

to remove legal uncertainty, a major obstacle for investments and for innovation in fledgling industries such as hydrogen. In an environment of transparent and stable regulations, investors will become more confident that their projects will live a full and productive life, which will both facilitate accessible allocation of capital and support the development of appropriate technologies. On the other hand, unclear or incomplete legislation can lead to delays, higher costs of operation, or may even discourage the participation of the private sector. For instance, ambiguous safety regulations and different certification standards of hydrogen equipment may raise compliance challenges and obstacles to market entry that make companies hesitate to invest in hydrogen activities. This lack of regulatory clarity stifles innovation and also hinders the commercialisation of hydrogen applications.

Regulatory certainty is also key to the simplicity of infrastructure building. Robust legal standards for licensing, safety, and environmental protection give developers access to otherwise cumbersome approvals. On the other hand, a lack of unified national policy, particularly for safety rules and environmental rules, can be an obstacle to critical infrastructure such as pipelines, hydrogen storage, and refuelling stations. Such delays can result in higher costs and lost opportunities for scaling the hydrogen economy. At the international level, regulatory coherence is required to enable the cross-border integration and trade in hydrogen. Harmonised regulations remove legal and technological barriers (in particular by facilitating the deployment of interconnected infrastructure) and, by implication, the scalability of worldwide hydrogen markets. Cross-border infrastructure integration is hindered, and the transport of hydrogen and related technologies is made more complex due to the lack of harmonised legal frameworks. When divergent safety and certification standards and trade rules prevail, transaction costs become problematic, and markets expand less readily. The establishment of



legal systems implementing uniform safety standards, certification measures, and trade rules creates market confidence and promotes international cooperation, which is important to develop a global hydrogen economy. The development of international regulatory agreements that bring about common safety requirements and certification systems is necessary to increase the certainty and consistency of the regulatory framework. International multilateral organisations like IPHE and IRENA are at the forefront of promoting regulatory certainty and stability globally and across the hydrogen supply chain. To achieve regulatory coherence, it is necessary to have binding international accords, regional agreements, and direct engagement of member countries in enforcing and reporting on adherence to international standards. Strong legal enforcement practices manage risks, secure investments, and contribute to the safe and healthy development of the hydrogen economy. Ultimately, leaning on the rule of law to help establish some legal certainty and uniformity would unlock the hydrogen economy to operate at its full potential. Through minimising any uncertainty, streamlining standards, and easing appetite for cross-border collaboration, workable regulatory frameworks provide the essential flywheel for the efficient scaling of hydrogen technologies and markets globally. Resolving the obstacles to regulatory convergence will be critical to establishing an integrated, robust, and sustainable world hydrogen economy.

7.2.5. Safety and security standards

Safety and security standards are a basic building block of the legal and regulatory regime of the hydrogen economy [19],[20]. Because hydrogen exhibits very different physical-chemical characteristics (e.g., a high degree of flammability, a wide flammability range, a low ignition energy, and a high diffusion rate), detailed and actionable safety directives are necessary. These procedures cover, among other things, explosion risks, difficulties

of detecting leaks and weaknesses of storage themselves that, if not addressed, could erode public confidence and slow market uptake. Strong safety and security requirements are thus indispensable for protecting both consumers and the environment as well as for allowing the safe penetration of hydrogen technologies into energy systems, transport, and industrial applications worldwide. The legal framework for safety issues of hydrogen is influenced by a mixture of national laws and international standards for the safe handling, transport, and storage of hydrogen. Relevant international standards are ISO 16111 for hydrogen fuel containers and IEC 62282 for fuel cell technology. International regulatory bodies and bodies like UNECE (United Nations Economic Commission for Europe) and ISO (International Organization for Standardization) have important functions in the homogenisation of safety standards beyond national borders. These bodies serve to develop a common understanding on safety, which in turn would lead to interoperability and mutual recognition of safety certifications." However, some gaps persist, in particular the alignment of national regulation and enforcement. Differing standards can lead to legal ambiguity, frustrating cross-border trade in hydrogen, and slowing the establishment of infrastructure in the sector's international integration.

With the growing inclusion of digital technology in hydrogen infrastructure, from automated production monitoring and remote refuelling station management to smart grid interfaces, cybersecurity becomes a fundamental aspect of safety and security. Cybersecurity legal requirements applicable to the energy system, such as the European Union's Network and Information Systems (NIS) Directive and the U.S. North American Electric Reliability Corporation Critical Infrastructure Protection (NERC CIP) standards, are gradually being extended to apply to hydrogen assets. Strong cybersecurity measures are required to secure the hydrogen infrastructure against cyber threats that may result in



disruption of operations, safety incidents, or environmental damage. As the global industry stakeholders, including national governments and international organisations, are shaping regulations and policing regimes that would require strengthening and reinforcing the cybersecurity of hydrogen safety systems, the line between physical safety and digital security is becoming more and more blurred.

Safety requirements are specific to the risk issues of each hydrogen application. In the transportation sector, e.g., hydrogen fuel cell vehicles have stringent requirements for the on-board hydrogen storage and for the safety of refuelling stations, under regulation, and protocols such as SAE J2601 for fuelling protocols. Safety factors for high-pressure storage and control of processes are necessary to avoid possible leakage and explosions in industrial applications of hydrogen. Safety zoning, monitoring, and emergency-response systems for public infrastructure, such as local fuel stations in the cities, as well as pipelines, are needed. New safety problems are rising with novel hydrogen technologies and their increasing usage, which must be considered by legislation. Emerging technologies, such as AI-enabled safety monitoring and high-end sensor networks, open new possibilities for improved observation and advanced risk detection responses. Future regulations will likely include these technologies as the NPS data promotes real-time safety monitoring. Economic, jurisdictional applicability, and timely technology updates are all legal considerations that may impact the adoption of hydrogen safety standards. National legal traditions and regulatory approaches differ, multiplying complexity for a multinational project development. But these struggles also pose opportunities for legal creativity. Advanced regulations coordination could be enhanced by creating standardised international safety regulations while promoting regulatory harmony and integrating new digital safety technologies would provide robust governance of hydrogen safety.

Progressive legal frameworks, striking the right balance between strict safety requirements and a degree of flexibility for innovative solutions, will be key to sustaining the growth of the hydrogen economy.

7.2.6. Incentives and Support for the Hydrogen Economy

The emerging nature of the hydrogen economy and its significant capital intensity and technological complexity necessitate strong legal and regulatory inducements to address initial market failures and encourage steady-state stability [21],[22]. Incentives and support mechanisms are geared toward stimulating investment, innovation, and deployment of hydrogen technologies and are available across a variety of financial and policy instruments. These mechanisms are orchestrated by legal constructs, which are predictable and supportive of broader energy and climate policies, underpinning an enabling environment for private sector engagement and public-private interaction. At the heart is incentives for the hydrogen economy, which works to lower the financial risk incurred when producing hydrogen and developing infrastructure, as well as when commercialising hydrogen technology through subsidies, grants, tax breaks, and preferential financing. These incentives are not merely theoretical inducements; they are inscribed into legal frameworks that provide for transparency and enforceability, which are in turn essential to attract long-term investment. By reducing upfront costs and the risks associated with operations, these incentives accelerate the development of hydrogen projects from pilot to full commercial scale, as the sector transitions toward maturity.

Various financial incentives have been launched by governments globally to spur the production and deployment of hydrogen. Subsidies and grants are frequently aimed at green hydrogen projects, which also require massive CAPEX investment in renewable-powered electrolysis. It pours billions of euros into its



Green Deal into hydrogen projects, with an emphasis on sustainability and innovation. The US Department of Energy's Clean Hydrogen Program also funds and offers technical assistance to promote hydrogen technologies in America. Australia's National Hydrogen Strategy involves government-supported grants and infrastructure spending to establish Australia as a global hydrogen supplier. These programs show how public funding can leverage private investment by mitigating project risk and increasing economic viability.

Another important and likewise preventive legal tool is tax incentives. ITCs, PTCs, and accelerated depreciation encourage capital investments in hydrogen infrastructure and technology. The United States' Inflation Reduction Act, for example, provides significant tax credits for clean hydrogen production depending on carbon intensity, rewarding technologies with low emissions. In addition to tax credits, green bonds and low-interest loans make even more capital available, with project developers not only accessing resources more easily, but obtaining them on the best basis as well. These types of instruments, which are typically de-risked by government guarantees or blended finance, are critical in bridging the financing gap between demo and commercial scale.

However, challenges remain with the realisation and maintenance of efficient stimulus incentives. Policy stability may be compromised by fiscal pressures, political changes, or bureaucratic bottlenecks, with consequent implications for investment certainty. There may also be fragmented or inconsistent incentives at the jurisdiction level that will limit the development of projects on a larger scale. Design of those mechanisms should take into account that the long-term sustainability will be achieved through gradual winding-down as the hydrogen economy matures and market competitiveness increases, avoiding sudden discontinuation, putting at risk the developments.

7.3. Future Directions

7.3.1. AI and Hydrogen Economy Law

Artificial Intelligence (AI) is suddenly becoming an impactful game changer in the hydrogen economy, presenting revolutionary prospects for enhanced production, distribution, and regulation of hydrogen technologies [23],[24]. Touted as a key technology in enhancing the efficiency of electrolyzers and supporting predictive maintenance of infrastructure, integration of AI into hydrogen systems has the potential to help increase operational performance, cut costs, and ease the integration of hydrogen into energy networks. This Part considers the complex intersection of AI and hydrogen economy law, including the legal structures needed to support the deployment of AI and the new regulatory challenges it creates. AI's contribution to the hydrogen economy is varied; the AI algorithms can process dynamic data from sensors that are installed throughout the system of electrolyzers, storage tanks, pipes, and refilling pumps to automatically calculate optimal operational parameters, including temperature, pressure, and energy consumption. This model-based optimization improves not only the hydrogen productivity but also the energy requirement and carbon emissions, in line with sustainability targets (EAI, 2024). Forecasting of hydrogen demand and renewable availability using AI-based models, allowing for the precise allocation and management of resources and supply chains. AI-based predictive maintenance solutions can detect equipment issues in advance, reducing equipment downtime and extending asset life, as illustrated by AI projects implemented in Germany's electrolysis plants.

AI's application to hydrogen systems also has significant legal implications. Data ownership and privacy become paramount concerns with the huge amount of operational data the network generates. Laws need to define data governance rights while



adhering to regional data protection laws, like the European Union's General Data Protection Regulation (GDPR). This involves creating means of sharing results with different groups of stakeholders in a manner that allows protection of company/individual proprietary and personal interests. Complications arise even further, in the form of liability and accountability. Because the use of AI may lead to autonomous decisions that influence the production of hydrogen or safety systems, the legal system will have to clarify responsibilities in case of breakdowns or accidents. And that requires developing liability doctrines that can accommodate AI's autonomy as well as the possibility that its algorithms get things wrong. Implications extend to ethical aspects such as algorithmic transparency, non-discrimination, and AI operations following sustainability and social responsibility principles. Regulatory adaptation is mandatory to govern the increasing role of AI in hydrogen technologies. The very legal frameworks currently in place, often conceived for traditional energy systems, must be modified to deal with AI-specific concerns, such as algorithmic accountability, cybersecurity, and real-time operational control. Regulators will need to develop standards and certification programs for AI-based hydrogen applications, striking a balance between encouraging innovation and safeguarding the public and the environment. International cooperation is vital to coordinate the regulations of AI in the hydrogen economy. AI for optimising the production and supply of hydrogen will develop cross-nation-level, requiring international standards for data interoperability, safety, and ethical use. IPHE and IRENA are organisations working to build consensus, share information, and create best practices to enable the most rapid deployment of hydrogen/FC technologies. Their activities facilitate the development of harmonised legal frameworks to ensure secure data exchange, joint innovation, and the integration of hydrogen markets across borders (IPHE, 2024). [jamil{Afzal, 2024 #1587}](#)

7.3.2. Digital Twin and Hydrogen Economy Regulations

The hydrogen economy is being reshaped by digital twin technology, as it allows for accurate virtual models of real-world hydrogen assets, including production facilities, pipelines, storage containers, and refuelling stations to be created [25],[26],[27]. These digital twins enable operators to monitor, simulate, and optimise the performance of entire hydrogen infrastructure in real-time, driving improved operational efficiency, safety, and scalability. Estimating performance by correlating sensor inputs with weather forecasting and system analytics, digital twins enable predictive maintenance, decrease downtime, and optimise energy management, which are essential towards driving the sustainability and economy of the hydrogen sector. The integration of digital twins into hydrogen systems raises intricate legal and regulatory issues. Existing legal frameworks will need to be developed to regulate the implementation of digital twin technology on critical hydrogen infrastructure, ensuring that safety, security, and data governance are robustly upheld. One of the biggest legal questions involves the ownership of and privacy with data. Digital twins require copious amounts of operational data, and who owns the proprietary rights to that data and where it resides are some of the issues to resolve across jurisdictions. This design challenge is evident in the trade-off between protecting commercially sensitive information on the one hand and sharing data between users to improve performance and safety. It is crucial to comply with specific data protection laws for a region (like GDPR for the European Union), which requires clear guidelines on how data is accessed, stored, and transferred.

Another important legal aspect is that of liability and accountability. Who is responsible if a system failure or an accident occurs when operational decisions, such as regulating the flow of hydrogen or triggering safety shutdowns, are advocated or made by digital twins? It poses such a challenge: the development of a legal



background, within which will be defined the duties for those who build and operate technology and those who supervise them, in particular in the case of the adoption of digital twins performing AI and automated control. Ethical issues also arise in this context and call for the transparency of the algorithms in digital twins' operations in order to avoid biases and to offer decisions that are compliant with safety, environmental, and social responsibilities. The efficient management of digital twin data is particularly important to enable interoperability and safety assurance. Only with harmonisation of data interchange standards and governance regimes can collaboration effectively span diverse actors and jurisdictions. International data collection, sharing, and storage standards will also need to be established and agreed upon to enable digital twins to operate with confidence in complex hydrogen networks. Regulatory requirements shall incorporate digital twin-based monitoring solutions as part of the oversight of hydrogen infrastructure to meet the requirements of the local and international safety standards. It also complements real-time risk detection and response capabilities, in turn improving operational safety. In real applications, there are several groundbreaking projects to prove the successful practice of the digital twin technology for hydrogen system utilisation. Already makes use of digital twins to manage the plant operation and maintenance, demonstrating the role that regulatory policy can play in promoting advanced digital monitoring while ensuring operating integrity. These use-case examples offer a glimpse into the legislation and regulation required to regulate the deployment of digital twins in a prudent fashion. Digital twin technology stands as a foundational innovation of the hydrogen economy with the potential for transformation on the dimensions of efficiency, safety, and scalability. But tapping this potential will depend on overarching legal and regulatory frameworks that encompass data governance, liability, safety standards, as well as cross-border cooperation. To facilitate

adaptive, harmonised legal frameworks that can facilitate the safe and sustainable deployment of digital twins in global hydrogen infrastructures, international cooperation and regulatory innovation will be key.

7.3.3. Law Research and Development

Research and development are indeed a pillar for the development and scaling up of the hydrogen economy. R&D activities are important to address technical, economic, and infrastructure issues, as hydrogen technologies move from test operations to broad commercialisation. The multidimensional complexity of hydrogen R&D encompasses a variety of natural and engineering sciences such as energy systems, materials science, chemical engineering, and transport infrastructure, which mirror the cross-cutting sectoral nature of the sector. Through innovation, R&D improves the efficiency, affordability, and reliability of hydrogen production, storage, and transportation to allow the hydrogen economy to reach its potential as an environmentally friendly source of energy. Hydrogen production is still a hot topic of R&D, with a large focus on the electrolysis processes. PEM and alkaline electrolysis technologies have witnessed rapid development, and many studies have focused on obtaining better catalyst efficiency, lower electricity consumption, and greater electrolyser durability. High-temperature electrolysis and biological production approaches are also candidate pathways toward cheaper and scalable solutions. Integration of renewable energy (e.g., wind, solar, geothermal power) with systems of hydrogen production is also a very important field of research, since it determines the economic profitability and environmental impact of green hydrogen [28]. For example, projects supported by the European Union's Horizon Europe programme have shown advanced coupling of variable renewables to electrolysers with better-tuned hydrogen output and grid stability.



Technologies for storage and long-distance transport are of equal importance. Considerable challenges exist for the large-scale implementation of hydrogen due to the low volumetric energy density of hydrogen, as well. R&D is developing high-density storage options (including liquid hydrogen and solid-state storage with metal hydrides or compressed gas storage). New materials, including carbon-based composites and high-strength alloys, are also being developed to improve the safety and efficiency of storage tanks. Furthermore, pipeline material and coating development are being studied to mitigate concerns of hydrogen embrittlement and leakage, which are important for the use of reliable and cost-effective transportation infrastructure. In the future, R&D in the context of the hydrogen economy will utilise the latest technologies, including AI, blockchain, and digital twins. Optimisation using AI can lead to more efficient production, predictive maintenance, and supply chain management. Blockchain provides secure, transparent certification systems for hydrogen origin and sustainability attributes. Real-time monitoring and simulation of hydrogen assets. Digital twins for safe and efficient operational management of assets. There may also be future breakthroughs in hydrogen storage materials, fuel cell efficiencies, system integration, or even carbon capture techniques, which may transform and accelerate the global deployment of hydrogen.

7.3.4. Infrastructure Development in the Hydrogen Economy

Infrastructure is essential for the creation of a scalable, sustainable hydrogen economy by providing the efficient production, storage, and transport of hydrogen. As hydrogen is linked to various industry sectors (such as energy, transport, and industry), the infrastructure for hydrogen must integrate well into systems for its impact to be maximised and its use to support the transition towards a low-carbon future. With increasing global efforts to move away from fossil fuels, hydrogen is seen as having

an important role in balancing supply and demand and for decarbonising hard-to-electrify, complex applications. It is essential to establish a viable, robust, scalable, and resilient infrastructure for the reliable generation and widespread use of hydrogen in a variety of sectors, including effective storage and distribution to meet the demanding requirements of end-users.

Similarity of equipment, exchanging, and standards are also crucial elements for the development of the sector. The construction of H₂ refuelling systems requires consideration of policy support, economic feasibility, social acceptance, and environmental influence. Local distribution networks will eventually connect industrial, commercial, and residential users, enabling universal penetration of hydrogen and encouraging a versatile hydrogen economy. An integrated legal and regulatory regime is essential for infrastructure development, including safety and licensing, and environmental regulation. International partnerships are looking to standardise regulations and have mutual safety and environmental regulations against projects that cross borders. Good policy support and incentives, including subsidies, tax credits, and grants, are essential to drive investment in infrastructure and advance hydrogen technology. Regulatory cooperation helps to facilitate the safe, accessible, and cost-effective investment in hydrogen infrastructure, in particular for cross-border applications that involve multiple jurisdictions' alignment. The establishment of hydrogen infrastructure is expensive, and it needs significant public and private investments to scale up. Public Private Partnerships (PPPs), VC, finance tools of development financial entities, Public resources, private capabilities, and private capital to get solutions. Government support and subsidies, green bonds, tax credits, and other financial incentives will be essential to attract private capital and reduce the risks related to next-generation hydrogen technologies.



The future of hydrogen infrastructure lies with advances in efficiency, cost reduction, and safety. Crucial will be developments in storage and transportation, advanced materials such as new composite and coating materials impervious to hydrogen embrittlement. Systems that can be produced in a modular way to scale flexibly and locally would provide more adaptable and sustainable infrastructure, especially in areas where resources and demand differ. The use of digital twins and other data-driven technologies (IoT, artificial intelligence, advanced monitoring) will ensure that hydrogen infrastructure is safe and efficient. Intelligent hydrogen sensors, flow meters for distribution monitoring, and predictive maintenance systems will help to make hydrogen networks more reliable and secure. Hydrogen hubs, or valleys As well as achieve scale and develop positive supply chain linkages through increased economies of scale and economies of scope, so reducing the cost of producing and using hydrogen. Sector cross-collaboration is driving the uptake of the hydrogen economy, which enables integrated solutions tackling multiple challenges at the same time.

7.3.5. Public Awareness and Education

Public information and education are key to developing a viable, sustainable hydrogen economy. As hydrogen technologies continue to develop and are increasingly used in global energy transitions, public opinion, knowledge, and acceptance will be key determinants in driving policy development, market use, and infrastructure (International Energy Agency-IEA, 2023). The greatest hydrogen solutions in the world could still run into resistance, or at least not realise their full potential, if not supported by informed and engaged communities. Social acceptability of Hydrogen systems is as vital as the technical one. Public awareness built on trust and acceptance is a driver for the use of hydrogen-based solutions, as societies shift away from fossil fuels to

renewable energy. Studies repeatedly conclude that public acceptance of new energy technologies is strongly determined by understanding and perceived advantage (IEA, 2023). It also drives the political and economic landscape and, with it, government policies, subsidies, and incentives necessary to scale the hydrogen economy (Hydrogen Council, 2022). Government-sponsored information and awareness campaigns have greatly helped foster public consensus about the role of hydrogen in decarbonization in jurisdictions such as Germany and Japan (IEA, 2023).

Both authorities and industry are essential to public awareness. Governments take the initiative in this regard by conducting information campaigns, educational programs, and community outreach methods, such as "the Basic Hydrogen Strategy" in Japan, including education of hydrogen in school curricula and promotion of public information concerning hydrogen (Ministry of Economy, Trade and Industry-METI, 2023). Industry players such as Air Liquide and Shell also contribute to local communities via their company campus activities, educational partnerships, and public-facing activities such as tours to hydrogen refuelling stations. Educational institutions, which include schools, colleges, and internet resources, are also a central part. The incorporation of hydrogen education into curricula at all levels is essential, with initiatives such as the European Hydrogen Valleys Partnership providing 'toolkits' of educational resources for schools (European Commission, 2022).

7.4. Role of International Law

It's international law that provides the essential framework for the global hydrogen economy [29],[30]. It provides the scaffolding for the alignment of legal rules for cross-border hydrogen trading, safety and environmental standards, and IP protection. The hydrogen laws should be integrated with



international digital laws to overcome the challenges of this digital era [31]. As hydrogen moves from a new energy carrier to a globally traded commodity, international treaties and multilateral treaties are necessary to create global market integration that can lead to ensuring that hydrogen production, transport, and storage technologies are regulated through standardised and predictable legal standards. Such a process is essential not just to overcome the challenges of legal fragmentation across nations but also to enable the safe, cost-effective, and environmentally acceptable development of hydrogen infrastructure. International actors such as IPHE, IRENA, UNFCCC, and UN bodies are key in building such globally accepted frameworks. For instance, the IPHE serves as a multilateral forum where governments work together to create common hydrogen safety guidelines and certification schemes. IRENA also provides technical and policy advice that facilitates the production of renewable hydrogen and its integration into national energy systems. The UNFCCC serves a bridging function by connecting hydrogen development to international climate change mitigation activities and by ensuring that the production of hydrogen fits into global decarbonization goals as established in the Paris Agreement. The Guarantee of Origin (GO) mechanism is a critical international legal tool to authenticate hydrogen's renewable character, especially in making sure that “green hydrogen” generated in one region is accepted as such by others. But the absence of an internationally recognised certification scheme for green hydrogen production is preventing international trade. International treaties and multilateral organizations need to develop systems for mutual recognition, allowing hydrogen to flow across world markets. Without these frameworks, this can lead to piecemeal access to the market and would detract from establishing an authentic global hydrogen economy.

Due to the emergence of hydrogen as a commodity to trade, international trade law will be instrumental in safeguarding cross-

boundary hydrogen transactions from national regulatory barriers. Trade law principles should be adopted to facilitate the free transport, exchange, and sale of hydrogen between countries, without encountering unjustified legal barriers or discriminatory actions. A strong global trade system also allows for mechanisms to settle any disputes that arise in cross-border hydrogen deals. The dispute resolution mechanism of the World Trade Organization (WTO) and “bilateral investment treaties” (BITs) are suitable to respond to trade barriers, regulatory divergences, and discriminatory treatment of the involved countries in hydrogen trade. For example, if one country wants to introduce tariffs or other trade barriers to imported hydrogen, the WTO’s dispute settlement body could be used to protect an open and fair hydrogen market. Also, BITs can serve as a means to protect investments in hydrogen infrastructure by being able to protect foreign investors from discrimination and undue treatment in the host state.

7.5. Conclusion

The hydrogen economy has reached an important crossroads in its development, and there is a growing demand for international legal architecture to catch up with the light-speed evolution of the technologies to produce, transport, and consume hydrogen. Significant legal issues to come in the field of hydrogen. The future legal challenges relating to the field of hydrogen will have to include IPR aspects as well, as hydrogen technologies become more specialized and exclusive. Jurisdictions will need to find ways to balance the protection of intellectual property with the desire to share knowledge globally, to speed technology development in the hydrogen space. Furthermore, the continued innovation in hydrogen storage, such as liquid organic hydrogen carriers (LOHC) and solid state, would require new regulatory models for safety, environment, and trade. For these technologies to



advance, international law may have to consider the adoption of new safety procedures and uniform standards in order to ensure that these innovations can be used safely and effectively across borders. With the time when hydrogen becomes commercial approaching, multilateral arrangements will have to be made to enable consistent regulation enforcement across boundaries. Monitoring and enforcement systems will be needed to oversee the production and trade of hydrogen and to ensure international sustainability and safety standards. As the international hydrogen market matures, international law will provide a foundation for the infrastructure, safety, and regulatory standards that will be necessary to enable hydrogen technologies to be integrated safely and efficiently into the global energy system.

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