CHAPTER TWO

INTRODUCTION TO HYDROGEN ECONOMY AND HYDROGEN AS A SUSTAINABLE ENERGY CARRIER

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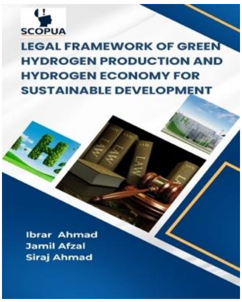

Book Title
Legal Framework of Green Hydrogen Production and Hydrogen Economy for Sustainable Development
Series Title
Books of Research Collection
Published On
August 16, 2025 (Edition 1)
Publisher
Scientific Collaborative Online Publishing Universal Academy, Lahore, Pakistan
DOI: https://doi.org/10.64060/978-627-7898-00-7-2
Book ISBN: 978-627-7898-00-7

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Abstract

The hydrogen economy represents a great transformation in how we produce, store, and use energy globally. It is not merely a technological shift but a comprehensive restructuring of energy systems, markets, and international trade. Hydrogen, a versatile energy carrier, is increasingly recognised as a key enabler in the global effort to decarbonise sectors that are difficult to electrify, such as heavy industry and long-distance transportation. At its essence, hydrogen serves as a clean energy carrier that can be produced from various sources and used across multiple applications. Unlike conventional energy sources, hydrogen's unique properties make it particularly valuable in transitioning to sustainable energy systems. When used in fuel cells, hydrogen produces only water as a byproduct, making it an attractive option for reducing greenhouse gas emissions. The International Energy Agency's Global Hydrogen Review 2023 estimates that hydrogen could contribute up to 20% of the total carbon emissions reduction needed to achieve net zero by 2050, particularly in sectors where direct electrification is challenging.

Keywords: *Green Hydrogen; Hydrogen Production; Hydrogen Production Methods; Hydrogen for Sustainable Development; Types of Hydrogen*

2.1. Defining the Hydrogen Economy

In heavy industry, for attaining high temperatures, hydrogen may offer an alternative to fossil fuels, for example, in the production of steel and concrete [1],[2]. Similarly, hydrogen fuel cells are a winning solution for long-distance transportation, where battery weight and charging take too long [3]. The European Commission Hydrogen Strategy states that these sectors currently represent approximately 30% of total global CO_2 emissions and that hydrogen adoption throughout these sectors could achieve dramatic reductions [4],[5]. The hydrogen economy is not only the future picture of the energy cycle but also serves as a common link to connecting various sectors in a sector coupling [6]. The integration of different energy carriers allows them to interact, unlocking possibilities for optimising energy systems by enabling energy to flow between sectors based on demand and availability

[7],[8]. Renewable electricity in excess can, for instance, be converted into hydrogen via electrolysis (a method that employs electricity to divide water resources into hydrogen and oxygen) [9],[10]. This step is vital for a hydrogen economy because it defines a new strategy to store excess renewable energy by transforming it into a stable and transportable substance. When renewable energy is not available, the stored hydrogen can be used for power generation or other applications at that time, thereby easing the intermittency challenges of variable renewable energy sources [11].

The hydrogen economy must be viewed in the context of a larger global climate action and sustainable development effort [12]. The RFI emphasises hydrogen's potential beyond emissions reduction and notes important energy security and economic development opportunities [13]. Hydrogen has the potential to help establish energy poverty solutions in sustainable communities, often in remote locations, the United Nations Development Programme says [14]. The move to a hydrogen energy system needs to address several issues; technical challenges comprise the establishment of effective production processes, secure storage facilities, and dependable transport mechanisms [15]. So, regulatory frameworks need to adapt to facilitate this transition but also maintain environmental integrity and safety. Key areas of regulation that will be explored in a lot more detail in later chapters include infrastructure development, safety standards, market mechanisms, international coordination, environmental regulations, and incentive programs. International legal frameworks influencing the development of hydrogen include key agreements and strategies. The foundations for action on global emissions, including in the field of low-carbon hydrogen technologies, are established in the Paris Agreement. The European Union sets a framework for hydrogen development across Europe for Production and Consumption Targets for Green Hydrogen [16]. One catalyst for international standards development is the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), which mobilises international and intergovernmental organisations to work towards harmonised standards and regulations [17],[18].

The hydrogen economy has the potential for addressing global energy and sustainable development challenges at the same time, for climate change mitigation [19]. It will only work if coordinated action is taken by different sectors and stakeholders, and that is supported by legal and regulatory frameworks [20]. It is a shift that requires innovation and creativity at every level, from policymakers to researchers to business leaders, as it will be seen as the backbone of a sustainable energy landscape in the future.

2.2. Hydrogen as a Clean and Sustainable Energy Carrier

Hydrogen plays a key role as a clean and sustainable energy carrier in the worldwide transition to low-carbon energy systems [21]. Hydrogen, especially green hydrogen, plays a crucial role in a deep decarbonization strategy [16]. This green hydrogen, made via electrolysis powered by renewable energy sources, is a stark contrast to traditional hydrogen production methods that require fossil fuels. Types of hydrogen production; this is important to know due to the environmental impact of hydrogen on this process. Grey hydrogen, made by steam methane reforming of natural gas, is the most widely used type today, but comes with high CO_2 emissions [22]. Blue hydrogen, also derived from natural gas, uses carbon capture and storage technology to lower emissions [23]. The most sustainable pathway is the production of green hydrogen via water electrolysis powered by renewable electricity, which has zero direct CO_2 emissions during production [24].

The role of green hydrogen in mitigating GHG emissions is clear across all sectors. In heavy industry and power generation, hydrogen can provide a clean substitute for fossil fuels, especially where direct electrification is difficult. For example, the carbon footprint of cement production processes can be lowered significantly through hydrogen use in high-temperature processes. Hydrogen can deliver flexible, dispatchable power through direct combustion in gas turbines as well as in fuel cells, thus balancing grids with high shares of renewable energy [25]. Hydrogen fuel cells are one of the forms of hydrogen power that provide a more sustainable option than fossil fuels and even battery electric solutions in many areas for the transport sector [26]. Heavy-duty ground transportation, shipping, and aviation face unique challenges for electrification due to weight and range constraints. Hydrogen fuel cells offer fast refuelling and long ranges, overcoming some of the barriers to the fast adoption of electric vehicles, especially in long-haul transport [27]. Hydrogen and ammonia are gaining recognition as energy and fuels with the potential to decarbonise the shipping sector, which currently generates around 3% of global CO_2 emissions, according to the International Maritime Organisation's Initial Strategy on Reduction of GHG Emissions from Ships [28],[29].

Hydrogen integration with renewable energy systems is one of the hallmarks of the modern energy transition. With these power-to-gas technologies, surplus renewable electricity can be converted to hydrogen, which can then be stored over long periods and used for power generation or other uses at a later time. In sector coupling, energy can be transferred between different sectors depending on demand and availability to optimise the energy systems. Integrating sectors with hydrogen can help maximise renewables within the energy system, even if they are intermittent, thereby optimising the carbon reduction potential of the entire energy system. The hydrogen economy will be inextricably linked to global climate agreements and sustainable development objectives. The Paris Agreement underpins the global response to climate change and, therefore, all pathways to develop the technologies for low-carbon hydrogen. The EU Hydrogen Strategy outlines a holistic framework for hydrogen deployment in Europe, with targets for the production and adoption of green hydrogen [30]. Such global frameworks shape the trajectory of hydrogen policy and market evolution, fostering an enabling landscape for investment and innovation.

In this case, it is direct policy instruments that are leading to market transformation. The stimulation plan under the EU Hydrogen Strategy has earmarked €470 billion of investments focusing on hydrogen production and infrastructure by 2030 [31],[32]. The US Inflation Reduction Act offers a production tax credit of $3 per kilogram of clean hydrogen, which could lower the cost of green hydrogen by as much as 50% in some places [33]. Germany is allocating €9 billion of its funding into its National Hydrogen Strategy, with a broad range of areas, including research, infrastructure, and market development [34]. Both of these policies are simultaneously creating market conditions that are sparking hydrogen and driving innovation and job creation. There are some key areas where the connection between policy instruments and technological evolution is clear. European funding programs have resulted in electrolyser costs at least 40% lower than in 2020, whereas US tax credits are helping to develop next-generation electrolyser technologies [35]. High-Performance Electrolysis German research activities are working on high-efficiency electrolysis; some of them are already a step ahead and have realised considerable advances in efficiency and stability. According to the World Economic Forum's Future of Hydrogen report, the global hydrogen market could be worth $2.5 trillion by 2050, generating millions of new jobs along the way [36]. This change in the economy is backed by coordinated government plans and policy tools. Carbon prices, reaching €90 per tonne as of October 2023 in the EU Emissions Trading System (ETS), are the direct prompt for hydrogen economics [37]. The Carbon Border Adjustment Mechanism (CBAM) reinforces this effect [38]: by implementing carbon costs on imported goods, the CBAM incentivises importing industries that want to stay competitive in international markets to shift towards low-carbon hydrogen [39].

Policy support has also helped fuel cell technology; Japanese government programs have helped to reduce the cost of fuel cell systems significantly [40]. EU research programs are researching new materials and new designs to improve new designs to improve performance and result in cost reduction. The US Department of Energy (DOE) is funding initiatives to increase the durability of fuel cells and reduce their platinum content, which will allow for cheaper and more sustainable technology [41]. Policy is also driving innovation in infrastructure. This includes the European Clean Hydrogen Partnership funding to develop innovative pipeline and storage solutions and the US Department of Energy programs to help develop hydrogen transport infrastructure. Asian Development Bank support will help build hydrogen refuelling networks throughout the region [42]. Hydrogen production and trade require international collaboration at scale. Through a variety of initiatives, such as the EU-Norway partnership on hydrogen production from offshore wind, the EU-North Africa hydrogen corridor leveraging the solar potential of North Africa, or the EU-Australia hydrogen trade and technology transfer deal, the EU has formed significant partnerships on hydrogen with third countries. Global projects such as the International Hydrogen Trade Forum (IHTF), the Global Hydrogen Flows project, and the Hydrogen Council's standards program are vital for developing common standards, fostering cross-border trade, and harmonising certification systems [43]. The hydrogen economy also inspires innovations in various sectors; everything from advanced materials for fuel cells to new electrolyser designs, the push for hydrogen technologies is sparking a new wave of tech development [44]. This innovation is not confined to the energy sector but also has implications for materials science, chemical engineering, and transportation technologies. As a result, technological progress can lead to the establishment of new industries and the transformation of existing ones, spurring economic development and job growth. Hydrogen is a versatile and powerful energy carrier with a bright future as a clean energy source [45]. Emanating from various sectors, hydrogen has the potential to address several challenges of global energy systems, from decarbonising hard-to-abate sectors to enabling the integration of renewable energy to assist with economic development. To fulfil that potential, however, will require urgent, coordinated action on multiple fronts.

Constant innovation in hydrogen technologies, supportive policies, and international cooperation will be essential to the successful implementation of comprehensive hydrogen strategies [46]. However, realising the potential can only happen through rapid, concerted action by all stakeholders. The transition to a hydrogen-based energy system is a strategic new building block to underpin a future carbon-neutral economy, and it is certainly not something one changes overnight; it is thus an immense strategic change in regards to forms of energy production, distribution, and consumption forms with significant effects in terms of the diffusion of climate change mitigation, energy security, and economic development [13],[47]. The challenge now is to catalyse investment alongside strategies that will help align technical, economic, and regulatory concerns while ensuring that the energy system transition to hydrogen is complementary to wider sustainability goals. Building the hydrogen economy is not just a question of technology; it will be a multi-faceted socio-economic transition that will require coordinated action across many sectors and stakeholders [48]. To realise this potential, governments, industry, and civil society need to work hand-in-hand to establish the right conditions for hydrogen to be the energy carrier of the future, one that is clean, safe, efficient, and sustainable. Such measures include finding appropriate policy means, researching and developing, building infrastructure, and international collaboration.

2.3. Integration of Hydrogen Energy

The importance of the hydrogen economy goes beyond being a clean energy carrier; it is a structural change in the ways that different energy sectors interact and combine [45]. This interlinking is around the keys to creating a sustainable and resilient energy system. A most valuable perspective on hydrogen and clean energy: Sector coupling: the hydrogen common energy carrier (HEC). This facilitates the interlinkage of the various energy generation, transport, and consumption sectors in multilinear processes, which was absent in the past. Integrating multiple energy sectors is key to ensuring high shares of renewable energy in the energy mix, according to the European Commission's updated 2023 analysis on this topic [49]. Hydrogen has unique properties that make it especially well-suited to these roles because it can be produced using diverse energy sources, stored for long durations, and used in multiple applications. Recent developments in electrolyser technology have lowered the cost of hydrogen production by up to 40% compared to 2020, according to the International Renewable Energy Agency (IRENA) [50]. Such developments are making power-to-gas technologies increasingly economical, removing barriers to renewable energy penetration. As with hydrogen generation, advances in fuel cell technology improve the efficiency of converting hydrogen back into electricity, and modern fuel cells are now achieving efficiencies of 60% or better. According to an analysis from the World Economic Forum, these cost reductions could make green hydrogen economically viable against fossil fuels in certain applications by 2030, especially when paired with carbon pricing mechanisms. According to the

International Renewable Energy Agency (IRENA), power-to-gas technologies could realise around 60% variable renewable energy combined in electricity systems by 2030 [51],[52]. The stored hydrogen can then be used for a variety of applications during periods of insufficient renewable energy generation. It could be converted to electricity via fuel cells or gas turbines, used directly in industrial processes, or transported to other sectors. Hydrogen storage could contribute as much as 20% toward the flexibility needs of European power systems by 2050, according to the European Network of Transmission System Operators for Electricity (ENTSO-E) [53].

2.4. Brief Economic and Environmental

The shift to a hydrogen economy has many advantages in environmental, economic, and social aspects. Not only are these benefits critical to tackling climate change, but they also promote sustainable development and generate new business opportunities. It is crucial to understand these benefits to formulate appropriate policies and strategies to advance the development of the hydrogen economy. The hydrogen economy offers perhaps its most promising aspect in terms of mitigating climate change, the environmental benefits. We believe hydrogen stands to decarbonise hard-to-abate sectors, which, as a critical pathway, serves as a means to reach global climate goals. Hydrogen also provides a clean substitute for fossil fuels in both steelmaking and cement, the two largest industrial sources of CO_2 emissions. The steel industry, for example, could use hydrogen in place of coking coal as a reducing agent, with the potential to reduce CO_2 emissions by up to 95% [54],[55]. In cement production, too, hydrogen could replace fossil fuels in kilns, which would substantially cut the sector's carbon footprint. The chemical industry could also use hydrogen as a clean feedstock, especially in ammonia production, which now contributes around 1% of global CO_2 emissions [56],[57]. Another area that represents a major opportunity for emissions reduction through hydrogen is the transport sector. Trucks, buses, and marine shipping, which also fall under the umbrella of heavy-duty transport, have been especially difficult to electrify because of weight and range constraints. Hydrogen fuel cells represent an effective alternative, with the ability to cut emissions by up to 90% in comparison to traditional diesel engines [58]. The maritime industry, which generates roughly 2.5 percent of global CO_2 emissions, may particularly gain from hydrogen-based fuels such as ammonia and methanol [29].

Hydrogen can also play a role in reducing emissions from power generation. The more renewables, such as wind or solar energy, take over the energy generation market, the more backup solutions you need to eliminate instances of low generation. Using fuel cells or hydrogen-fired turbines, hydrogen can serve this role, providing a clean alternative to natural gas peaking plants. Hydrogen is also connected to many of the Sustainable Development Goals (SDGs), especially SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) [59],[60],[61]. Hydrogen enhances the transition to sustainable energy systems by facilitating the integration of renewables and offering low-emission energy solutions across multiple sectors. Hydrogen can contribute to several Sustainable Development Goals (SDGs), such as SDG 9 (Industry, Innovation and Infrastructure) and SDG 12 (Responsible Consumption and Production), according to the United Nations Development Programme (UNDP) [60],[61],[62]. The Middle East and North Africa (MENA) region, blessed with near-endless solar sources, is surfacing as a player in green hydrogen production, with developments such as Saudi Arabia's NEOM Green Hydrogen Project and the Omani Hydrogen Alliance highlighting the region's potential for hydrogen exportation. These, in terms of economy, go even further, towards regional development. Areas with rich renewable resources can use these to generate green hydrogen, developing new sectors and jobs. Hydrogen can enhance air quality and mitigate health impacts by minimising air pollution arising from fossil fuel combustion. According to the World Health Organisation (WHO), air pollution is responsible for 7 million premature deaths worldwide each year, as well as significant economic costs [63]. Shifting towards hydrogen-based energy systems could help mitigate these impacts, especially in densely populated urban centres and industrial zones. The environmental advantages, especially from an emissions reduction and climatic point of view, are essential to attain the global climate targets.

2.5. Challenges in the Hydrogen Economy

The idea of a hydrogen economy is compelling, but there are immense hurdles to overcome before we can unlock its potential. These challenges range from technical to economic and regulatory, but all require coordinated solutions. Comprehending such challenges is imperative for formulating strategies to overcome them for the successful implementation of hydrogen-based energy systems. The first key obstacle in the development of the hydrogen economy lies in the technology development; it is too technically challenging to scale up green hydrogen production. Current electrolyser technologies, though continuously improving, still suffer from limitations with efficiency and capital costs. IRENA estimates that a level of improvement in electrolyser efficiency is needed to make green hydrogen cost-competitive with traditional fuels, a 20% increase at a minimum [64]. Renewable energy sources employed in electrolysis are volatile; this added time frame would encourage stable production levels and energy use optimisation [65].

Following these production challenges, another set of technological challenges relates to the storage and transportation of hydrogen. The energy density of hydrogen is low, and hydrogen is physically different from conventional fuels; transport and storage are therefore inherently more complex than those of existing fuels. Existing storage techniques, like compressed gas and liquid hydrogen, lead to energy density, safety, and cost issues. Advancement of state-of-the-art storage technologies, such as metal hydrides and chemical carriers, is still in the burgeoning process; and infrastructure, such as for long-distance hydrogen transport, implies major capital and technological investment. A study by the European Commission's Joint Research Centre highlights the "need for specialised infrastructure, such as dedicated pipelines and storage," as "one of the key barriers to large-scale hydrogen deployment". These tech challenges, coupled with energy efficiency considerations spread across the hydrogen value chain, further complicate things. Electrolysis itself is only 60-70% efficient, and further energy losses occur in storage, transport, and conversion [66]. The overall efficiency of the hydrogen value chain, according to the International Energy Agency (IEA), will need to increase by a factor of three or more in order to compete with direct electrification in many applications [67]. This is most acute in those sectors where some form of direct electrification would be possible, in which hydrogen needs to be more efficient and inexpensive to beat out other solutions.

Although the technological challenges are substantial, they are intimately connected to economic hurdles that need to be tackled concurrently. Economic issues pose another significant challenge to the evolution of the hydrogen economy. Cost has also been a major concern, as green hydrogen is still between two and three times as expensive as conventional fuels. According to the Hydrogen Council, it is expected that production costs will need to be 60-80% lower compared to fossil fuels by 2030 to reach cost parity [50]. This reduction must derive from a range of sources, including technological innovation, economies of scale, and lower renewable energy costs. These cost reductions will depend on the scaling of production facilities and the formation of hydrogen hubs; beyond production costs, the economic challenges go all the way to the need for investment and funding. Hydrogen economy funding and investment needs are massive. To meet climate goals, global investment in hydrogen infrastructure must reach $1.2 trillion by 2030, according to the IEA [68]. Their investments of this magnitude are only attracted where there are clear policy signals and financial incentives. Carbon pricing mechanisms, subsidies, and tax incentives can close the cost gap between hydrogen and conventional fuels. The Energy Sector Management Assistance Program (ESMAP) of the World Bank has stressed the need for innovative financing mechanisms and risk-sharing arrangements to mobilise the requisite capital [69],[70].

Due to these economic challenges, regulatory and policy obstacles must be overcome before a suitable environment for hydrogen development is created. The development of the hydrogen economy is also complicated by regulatory and policy challenges. Part of that is going to be harmonising standards across various jurisdictions for a truly global hydrogen market. But at the moment, there is no internationally agreed-upon framework for hydrogen certification, safety standards, or quality specifications. Uncoordinated or insufficient standards create confusion for investors and act as a barrier to the growth of international hydrogen trade. Then, some legal barriers hamper the so-called hydrogen trade between the nations, making the regulatory landscape even more complicated. Cross-border hydrogen trade is now subject to further legal obstacles. Previous international trade agreements and energy regulations were developed without hydrogen in mind, and so it remains unclear how, or even if, they apply to hydrogen trade. The World Trade Organisation (WTO) is considering how existing trade rules apply to hydrogen, especially when it comes to subsidies and environmental standards [71]. In short, both the establishment of specific hydrogen trade agreements and the repurposing of existing energy infrastructure that can be used to transport green hydrogen on a commercial scale will require thoughtful legal nuance and international collaboration.

2.6. Legal and Regulatory Framework for Hydrogen

A sound legal and regulatory regime is also necessary for the effective operation of a hydrogen economy. With the transformation of hydrogen from a small-scale to a large-scale energy vector, there is an emerging need for consistent and structured legislation. The worldwide regulatory environment for hydrogen is not homogeneous enough, which creates barriers to the development of a global hydrogen market. The lack of international norms regarding hydrogen production, transport, and use also makes investors risk-averse and limits cross-border trade. One approach to filling this gap is that the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) and the International Organisation for Standardisation (ISO) are making efforts in standards for hydrogen technologies on a global basis [72],[73]. Some 200 current standards for hydrogen applications have been compiled according to the IPHE's Technical Advisory Group on Standards and Regulations, although not all are fit for purpose in a large-scale hydrogen economy and will require revising or recasting [74]. Developing consistent certification criteria for green hydrogen is also critically important, as it will ensure market participants have clarity and transparency while upholding the environmental integrity of hydrogen solutions. These global standards provide a basis for overcoming the complex legal and practical issues associated with cross-border hydrogen commerce.

A hydrogen certificate system and carbon pricing method must be established to ensure fair market competition. Certified schemes should separate types of hydrogen (green, blue, and grey) by their carbon intensity and production method. The RED II offers a certification of renewable hydrogen, including conditions of additional value (additionality) and temporal correlation of renewable electricity production with hydrogen production [75]. Carbon pricing instruments such as carbon taxes and emissions trading systems (ETS) are instrumental for the development of low-carbon hydrogen technology [76]. The European Union ETS and equivalent measures by other authorities provide a level playing field for clean hydrogen by internalising these environmental costs of the fossil fuel alternatives [77]. Supportive regulatory frameworks for hydrogen development. A supportive legislative environment for the development of hydrogen is being established by national and regional policies. Following the EU's Hydrogen Strategy adopted in 2020, it sets out a full framework for hydrogen in the EU, with binding and clear targets for hydrogen production and use [4]. And the Basic Hydrogen Strategy of Japan and the Hydrogen Economy Roadmap of South Korea show examples of how countries are creating national plans for hydrogen policy. Included in these efforts are several policy tools, such as subsidies, tax credits, and grant programs, to help stimulate private sector investment in hydrogen technologies and infrastructure. The United States Inflation Reduction Act of 2022 contains huge incentives for clean hydrogen production, which shows that policy regimes can incite the capital to flow to hydrogen technologies [78].

Given that international standards will be required, cross-border trade of hydrogen raises challenging legal issues that require solving. The lack of consistent standards is having a direct influence on the development of dependable international hydrogen trade systems. The current international trade treaties, as well as energy legislations, were not prepared in consideration of hydrogen trade, and uncertainty remains on whether those legal frameworks might be applied to hydrogen trade. The World Trade Organisation

(WTO) is also looking into how current trade rules are relevant to hydrogen, in particular on the question of subsidies and environmental standards. The conversion of existing infrastructure pipelines and storage to accommodate hydrogen use needs to be legally tackled in a judicious manner in many countries in international cooperation. The European Union's TEN-E (Trans-European Networks for Energy) regulation, which has been expanded to cover hydrogen infrastructure, offers an example of how existing rules can be morphed to apply to hydrogen trading [79]. Bilateral agreements, like the EU-Norway hydrogen cooperation framework, illustrate how regional cooperation can promote hydrogen trade while addressing specific regulatory issues. Effective hydrogen regulation needs international cooperation to frame and implement appropriate rules. The Clean Energy Ministerial's Hydrogen Initiative connects governments, industry, and research to advance hydrogen technologies and policies [80]. The IPHE is a major enabling mechanism for international cooperation, sharing best practices, and the development and harmonisation of standards. Another key platform for international collaboration is the IEA Hydrogen Technology Collaboration Programme, an organisation that promotes, develops, and coordinates (public and private) efforts in research, development, and demonstration projects in hydrogen technologies. Such collaboration is critical to addressing the global nature of hydrogen markets, and regulation enables the advancement of the hydrogen economy.

Long-term policy certainty is also required to attract the significant private-sector investment required to scale the hydrogen economy. Policy uncertainty can delay the processing of large-scale hydrogen projects and inhibit the expansion of hydrogen demand. Indeed, the International Energy Agency's review of hydrogen investment trends suggested that the commitment to substantial private-sector finance would rely on robust, long-term policy frameworks. In areas where the policy environment is less stable, hydrogen projects are not as advanced, illustrating the value of stable and certain regulatory regimes. Regulations relating to safety are an important part of the legal framework of hydrogen. Its special characteristics, high flammability and low ignition energy mean that special safety measures must be taken for the production, storage, and transport of hydrogen. The International Electrotechnical Commission (IEC) and ISO have also established broad safety standards for hydrogen technologies, including material compatibility, pressure vessels, and hazard analysis. The European Union's Pressure Equipment Directive (PED) and corresponding regulations elsewhere deliver the means to ensure the safe filling and use of hydrogen [81]. Safety standards must be developed at the same speed as the technology develops, especially when it comes to hydrogen filling stations and large-scale stores.

2.7. Future Outlook of the Hydrogen Economy

The growth of the hydrogen economy is anticipated to be led by technological progress. For hydrogen specifically, substantial cost reductions are expected for electrolyser technology, anticipated to be 40-60% cheaper by 2030 (IRENA) [50]. Material science and process engineering development are anticipated to enable electrolyser efficiencies to rise from today's level (60-70%) to above 80%, which increases the economic attractiveness of green hydrogen production [82]. The progress of high-temperature electrolysis and novel catalyst materials would be helpful in improving efficiency and energy consumption. In fuel cells, continued exploration of novel materials and design configurations will result in improved longevity and decreasing costs that will make hydrogen fuel cells more competitive with other methods of power production. Yet tapping these technological opportunities does not come without the challenges of scaling up production, the strength of supply chains, and the consistency of quality between global markets. Based on these developments in production, breakthroughs in hydrogen storage and transport are needed to resolve the limitations to be resolved. The solid-state approach, including metal hydrides and chemical hydrogen storage, emerges as a demanding option for energy storage and safer systems. The concept of liquid organic hydrogen carriers (LOHCs) holds the promise to make hydrogen transport safer and more efficient over long distances [83]. Market expansion and investments in the hydrogen industry are forecast to skyrocket in the next few decades. The Hydrogen Council estimates the world could supply one-fifth of its energy needs with hydrogen by midcentury, and the market could be worth almost $2.5 trillion by 2050, producing more than $2.5 trillion worth of products annually [84]. Private sector participation is instrumental to this expansion, with the world's leading energy companies and industrialists increasingly capitalising on hydrogen technologies. Political incentives, including carbon price and production support, will be crucial to stimulate such investment. The EU Innovation Fund and other such programs in other geographies are acknowledging and using government support to bootstrap private investment in hydrogen technology. The impact of such investments is likely to be limited unless supported by consistent and long-term policies, therefore enhancing policy predictability and discouraging stops and starts, which may erode the private sector's willingness to participate.

Prospects of Global Hydrogen Trade Although it is small and marginal now, the potential of global hydrogen trade will gradually expand along with the falling production cost and infrastructure construction. According to the International Renewable Energy Agency (IRENA), global trade of hydrogen could hit 150-200 million metric tonnes per annum by 2050, with significant trade corridors opening between resource-abundant areas and demand centres [84]. Establishing hydrogen trade agreements and international standards will be key to enabling this trade. The EU's Hydrogen Import Strategy and comparable programs in other parts of the world are just some examples of how countries are starting to pave the way for hydrogen trading. However, the full potential of this world trade will be dependent on a resolution of policy discrepancies between regions and on the coherence of the regulatory paradigm across borders. Infrastructure is another obstacle, as it would require massive investment in production plants, storage systems, and transportation infrastructure. Policy coordination will be key if the world is to establish an investment-friendly environment and experience smooth international trade. Divergences among regional policy responses, ranging from ambitious hydrogen strategies in place in the European Union to more modest building blocks in place in some developing countries, may raise obstacles to forging a truly global hydrogen market. The future of hydrogen as an energy carrier is a consequence of the interaction of technological, economic, and policy drivers. Further, fundamental science and technological innovation will be required to improve the technologies for the production, storage, and utilisation of hydrogen. Strong policy backing and international cooperation will be needed to establish the market psychology and infrastructure. The realisation of the hydrogen economy will depend on the concerted effort from governments, industry, and research institutions to solve the remaining problems and clear uncertainties. Despite the challenges, the rewards of a successfully developed hydrogen economy, with its key contributions to solving climate change and achieving sustainable development, render it a fundamental part of the world's energy evolution. The coming decades will be a critical period in defining whether hydrogen can realise its potential to become a linchpin for a sustainable energy future.

2.8. Conclusion

The hydrogen economy is positioned as an important part of the transformation to sustainable and low-carbon energy systems around the world. As discussed throughout this chapter, the ability of hydrogen to decarbonise high-emitting sectors such as heavy industry, transport, and the power sector emphasises its importance in helping pursue global climate objectives. According to a report from the International Energy Agency, hydrogen has the potential to deliver 20% of the total CO_2 emissions reductions required to meet a net-zero target by 2050, especially for the most difficult-to-decarbonise sectors. This potential has made hydrogen an important prospect on a global energy map, having implications for both industrialised and developing countries. With innovations, particularly around green hydrogen, storage, and fuel cell technology, the long-term scaling up of the hydrogen economy is possible. International cooperation and harmonised regulatory schemes will be essential if hydrogen is to reach its full potential as the clean energy age dawns. The establishment of international standards, cross-border trade arrangements, and harmonised policies will be key to enabling an attractive business and investment climate and promoting the development of the hydrogen economy. The EU Hydrogen Strategy, the Japanese government's Basic Hydrogen Strategy, and similar efforts in other regions show that hydrogen is increasingly recognised as a key part of the energy transition. However, differences in regional policy pathways, as well as the requirement for investment certainty through long-term policy frameworks, underline the importance of global collaboration to deliver hydrogen's full potential.

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