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LEGAL FRAMEWORK OF GREEN HYDROGEN PRODUCTION AND HYDROGEN ECONOMY FOR SUSTAINABLE DEVELOPMENT

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Legal Framework of Green Hydrogen Production and Hydrogen Economy for Sustainable Development

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Authors Biography

Ibrar Ahmad is a PhD scholar in law at Southwest University of Political Science and Law, China, specializing in climate justice, environmental governance, and the legal frameworks that support sustainable development. His academic work addresses critical global challenges, with a particular focus on the role of legal structures in climate action and green energy transitions. Ibrar has contributed to a range of peer-reviewed journals, exploring judicial activism, environmental protection, and the legal implications of emerging technologies. His research also delves into the intersection of law and sustainability, highlighting the need for more effective global governance in addressing environmental issues. In addition to his academic achievements, Ibrar is an experienced lawyer currently practicing in China. He has worked with prestigious law firms, including his role as an associate advocate at King and Capital Law Firm in China, where he combines his legal expertise with cross-border legal practice.

Dr. Jamil Afzal has been involved in research and teaching for various National and International institutes for more than ten years. He is the author of three books and a contributor/associate editor in two others, as well as the author of various high-ranking journal articles; he has also participated in reputable international conferences. He is an expert in Digital Law, the Digital Economy, the Hydrogen Economy, and the Legal Phenomenon of Digitalization. Dr. Jamil Afzal founded Contemporary Theory of Digitalization (CToD); CToD consists of three levels, including 3Ds at the first and 5Ds at the second level, and 7Ds at the third level. He is the Principal Ethical Editor at the International Research and Publishing Academy (IRAPA) for its associated journals, and the Executive Director at Ahbab Lawer Forum & Research Society. He is the academic editor of PLOS ONE Journal, along with a peer reviewer of different international journals. He is listed in the top 2% of scientists working on “legal fundaments” (RIS of Dr. Jamil Afzal is higher than 98% of researchers working on “legal fundaments” around the world-RG Ranking 2025).

Siraj Ahmad is a Ph.D. scholar in Chemical Engineering at Tianjin University, specializing in advanced membrane technologies for N_2/CH_4 gas separation. He conducts his research under the supervision of Professor Wang Zhi at the Chemical Engineering Research Center and the Tianjin Key Laboratory for Membrane Science and Desalination Technology. His work focuses on the design and development of high-performance mixed matrix composite membranes for energy-efficient gas separation processes. In addition to his doctoral research, Siraj contributes extensively to the Advanced Instrument Analysis and Testing Center, part of the School of Chemical Engineering and Technology at Tianjin University. Here, he supports research and education by assisting visiting scholars and international researchers with advanced analytical techniques and instrumentation. Siraj's work reflects a strong commitment to innovation in membrane science, sustainability in gas separation, and international academic collaboration.

Foreword

As a professor with a particular research interest in environmental law and a dedicated practitioner in this field, I am both privileged and honoured to lead my student Ibrar Ahmad and collaborate with other two renowned scholars to complete this work. This work stands out as a pioneering initiative, bringing together a wealth of crucial information on a topic of increasing significance in today's global energy transition.

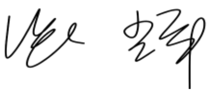
Legal frameworks governing hydrogen economies are varied and complex, shaped significantly by government policies, statutory provisions, safety regulations, and investment incentives. These legal regimes influence key aspects of hydrogen development, from project permitting and environmental compliance to market access and investment opportunities. Notably, while established economies have made strides in developing regulatory structures, emerging economies, especially in Asia and Africa, are still grappling with significant legal challenges. Issues such as legal uncertainty, fragmented regulatory landscapes, and infrastructure deficits present considerable barriers to the widespread adoption of hydrogen technologies.

This book delves into the legal impediments that must be addressed to unlock the full potential of hydrogen, particularly in regions where opaque investment protection laws, fragmented policy frameworks, and the absence of coherent hydrogen strategies present substantial hurdles. These challenges are not just theoretical but present real risks of delaying or even obstructing the creation of hydrogen markets in key regions. Furthermore, the role of international agencies, such as the International Renewable Energy Agency (IRENA) and the International Energy Agency (IEA), is crucial in fostering the development of harmonised regulatory structures that support hydrogen deployment worldwide.

Regulatory fragmentation remains a major concern, and the collaborative efforts of these agencies will be essential to facilitate the creation of a cohesive, globally integrated hydrogen market. Their work is pivotal in tackling legal and regulatory fragmentation across jurisdictions, ensuring the smooth and efficient operation of hydrogen markets in the future. The book explores the necessary legal responses to these issues, particularly with regard to the development of international certification standards for hydrogen and the creation of adaptive regulatory models that can accommodate emerging technologies and evolving business models.

From an environmental law perspective, the significance of these legal frameworks becomes even more profound. As the hydrogen industry grows, legal structures must not only facilitate economic and technological advancements but also ensure that environmental sustainability is prioritised. The regulatory frameworks that support the hydrogen economy must be adaptable to respond to emerging environmental concerns and ensure compliance with global sustainability standards. The case studies included in this book, along with explanations of key legal terms and discussions of the unique challenges faced by developing countries, offer an insightful and practical perspective on how the law can shape and support the global hydrogen transition in an environmentally responsible manner.

Finally, this book highlights the crucial importance of international legal cooperation, policy harmonization, and regulatory flexibility in enabling hydrogen to play a central role as a clean energy vector in the global transition to a sustainable energy system. This work will be of great interest not only to legal professionals and their advisers but also to marketers, policymakers, and administrators engaged in the planning and implementation of hydrogen-related projects at both national and international levels. The insights contained within will prove invaluable in guiding the future of hydrogen law and policy, with a strong focus on promoting environmental sustainability.



Prof. Zhang Hui
Southwest University of Political Science & Law, China

Preface

This book provides a deep insight into the Hydrogen Economy and its regulatory framework. The emergence of the global green hydrogen economy poses a complex legal challenge, requiring the development of flexible and holistic legal frameworks to support new technologies within unique sectors and among various legal systems. From fledgling novelties to indispensable elements of energy systems worldwide, hydrogen technologies are about to transform, and legal frameworks will play an essential role on a rugged regulatory terrain to goad investment, to guarantee safety, and to support a sustainable in-place. The complexity of hydrogen's production, transport, storage, and use needs consistent regulation to facilitate smooth integration into the industrial, transport, and energy sectors.

The absence of internationally recognised certification and varying uptake of technical standards are obstacles to integration in the market and potentially undermine public confidence. There is also an unresolved tension between the speed of deployment and meaningful stakeholder engagement, in particular, when projects are being fast-tracked on the grounds of higher public interest. In the future, the shift towards a global hydrogen economy will rely on a convergence of national legal regimes with global norms, adapted to local circumstances. Harmonisation activities arranged by bodies like ISO, IRENA, or IEA are very important for the acceptance of common definitions, certification procedures, and safety requirements. Bilateral and multilateral relationships and harmonisation of domestic regulation towards international best practice will play a key role in supporting efficient and transparent cross-border hydrogen flows.

But harmonisation also has its dangers; the danger of regulatory "race to the bottom," erosion of national policy autonomy, and how to tradeoff between rigour and flexibility all need to be deftly handled. Policymakers should focus in particular on establishing solid, evidence-based certification schemes, open and inclusive stakeholder involvement, and the adjustability of the legal frameworks to changes in technology and markets. In the end, the legal structure surrounding the hydrogen economy should be flexible as well as principled, creating the conditions for innovation and investment without compromising on environmental and social aims. With the lesson of comparative experiences acting as reminders to stay committed to international cooperation, the world can speed up the transition to a sustainable, integrated hydrogen economy -- one that materially supports climate ambitions, energy security, and economic opportunities.

Dr. Jamil Afzal

Dedication

Authors are thankful to the dedicated editorial staff at Scientific Collaborative Online Publishing Universal Academy (SCOPUA). Dedication goes to Mian Muhammad Afzal (Advocate High Court Lahore) for his patience and guidance during the long hours spent writing this book. Finally, our most sincere thanks go to our families for their support.

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Table of Content

List of Abbreviation

ACER Agency for the Cooperation of Energy Regulators
ASCM Agreement on Subsidies and Countervailing Measures
CBD Convention on Biological Diversity
CFR Code of Federal Regulations
DOT Department of Transportation
ECJ European Court of Justice
EPA Environmental Protection Agency
FERC Federal Energy Regulatory Commission
GATT General Agreement on Tariffs and Trade
HFTO Hydrogen and Fuel Cell Technologies Office
IEC International Electrotechnical Commission
ISO International Organization for Standardization
LCFS Low Carbon Fuel Standard
MEA Multilateral Environmental Agreements
NFPA National Fire Protection Association
OECD Organisation for Economic Cooperation and Development
PHMSA Pipeline and Hazardous Materials Safety Administration
TBT Technical Barriers to Trade
UN United Nations
UNFCCC United Nations Framework Convention on Climate Change
US United States
WTO World Trade Organization
AEM Alkaline Anion Exchange Membrane
ASU Air Separation Unit
ATR Autothermal Reforming
AWE Alkaline Water Electrolyzer
CCS Carbon Capture and Storage
CCUS Carbon Capture, Utilization, and Storage
CH_4 Methane
CO Carbon Monoxide
CO_2 Carbon Dioxide
CPU CO_2 Compression and Purification Unit

GWP Global Warming Potential
H_2 Hydrogen
H_2O Water
H_2S Hydrogen Sulfide
HHV Higher Heating Value
HTSE High-Temperature Steam Electrolyzer
KOH Potassium Hydroxide
LCOE Levelized Cost of Energy
MP Methane Pyrolysis
NaOH Sodium Hydroxide
NPP Nuclear Power Plant
O_2 Oxygen
PEM Proton Exchange Membrane
PSA Pressure Swing Adsorption
PV Photovoltaic
SMR Steam Methane Reforming
SOE Solid Oxide Electrolyzer
SOEC Solid Oxide Electrolysis Cell
TRL Technology Readiness Level
AFIR Alternative Fuels Infrastructure Regulation
AGHA Africa Green Hydrogen Alliance
AIIB Asian Infrastructure Investment Bank
APac Asia-Pacific
CISG United Nations Convention on Contracts for the International Sale of Goods
GH2L Green Hydrogen Legal Capacity Unit
GTR Global Technical Regulation
IHTF International Hydrogen Trade Forum
MDB Multilateral Development Bank
UNECE United Nations Economic Commission for Europe
UNIDO United Nations Industrial Development Organization
AI Artificial Intelligence
CIP Critical Infrastructure Protection
EPO European Patent Office
GDPR General Data Protection Regulation
IoT Internet of Things
IP Intellectual Property
ITC Investment Tax Credit

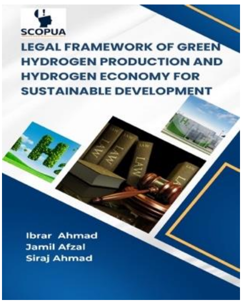
NERC North American Electric Reliability Corporation
NIS Network and Information Systems
PCT Patent Cooperation Treaty
PTC Production Tax Credit
SAE Society of Automotive Engineers
WIPO World Intellectual Property Organization
BAT Best Available Techniques
CCfD Carbon Contracts for Difference
CfD Contracts for Difference
DNV Det Norske Veritas
GH_2 Green Hydrogen Standard
GO Guarantees of Origin
IED Industrial Emissions Directive
OSHA Occupational Safety and Health Administration
PPA Power Purchase Agreement
RED Renewable Energy Directive
RFNBO Renewable Fuels of Non-Biological Origin
RMP Risk Management Program
TEN-E Trans-European Networks for Energy
UVPG Environmental Impact Assessment Act
BIL Bipartisan Infrastructure Law
CBAM Carbon Border Adjustment Mechanism
DoE Department of Energy
ENTSO-E European Network of Transmission System Operators for Electricity
ESMAP Energy Sector Management Assistance Program
ETS Emissions Trading System
EU European Union
FTC Federal Trade Commission
IEA International Energy Agency
IPHE International Partnership for Hydrogen and Fuel Cells in the Economy
IRA Inflation Reduction Act
IRENA International Renewable Energy Agency
MENA Middle East and North Africa
NDC Nationally Determined Contributions
RD&D Research, Development, and Demonstration
SDGs Sustainable Development Goals
SEC Securities and Exchange Commission

UNDP	United Nations Development Programme
WHO	World Health Organisation
HESC	Hydrogen Energy Supply Chain
PLI	Production-Linked Incentive
TransHyDE	Transport and Transformation of Hydrogen

CHAPTER ONE

AN INTRODUCTION TO DIFFERENT TYPES OF HYDROGEN AND METHODS OF GREEN HYDROGEN PRODUCTION

IBRAR AHMAD [1], JAMIL AFZAL [2]* AND SIRAJ AHMAD [3]



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Abstract

Hydrogen is gaining prominence as an important clean energy carrier with the potential to cause a transformation in the world as it shifts to sustainable, low-carbon energy systems. In this chapter, the author will provide a vivid description of the various types of hydrogen, distinguished by their production technologies and environmental friendliness, including grey, blue, turquoise, pink, and green. The focus is on green hydrogen produced through the electrolysis of water by using renewable energy sources, including solar and wind. Green hydrogen is a zero-emission solution with huge potential to decarbonise sectors that are difficult to electrify, such as heavy industry, transportation, and power generation. The chapter discusses important technologies of green hydrogen production, such as proton exchange membrane (PEM), alkaline, and solid oxide electrolysers, and further advanced systems such as PV/T-electrolysis, wind-electrolysis, biological, and thermochemical processes. The efficiency, scalability, cost, and renewable energy integration are considered with regard to each technology. In addition, the paper discusses the key obstacles to green hydrogen, including the high cost of production, infrastructure requirements, and technology maturity. Nevertheless, with the increasing global emphasis on net-zero goals, a drop in renewable energy prices, and a swift technological improvement, green hydrogen can become the foundation of a clean energy future economy.

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

1.1. Introduction

The increase in global energy demand that is clean, secure, and sustainable energy has influenced the increased rate of abandoning fossil fuels [1]. In this regard, hydrogen has turned out to be a strategic energy carrier that could transform many energy systems in the transport, production, electricity, and chemical sectors [2]. It is versatile because Hydrogen can store, transport, and deliver clean energy when generated using renewable energy sources [3]. An example is the hydrogen fuel cell, which produces only water and heat and thus is very appealing as a zero-emission solution, both in mobile and stationary applications. In addition, hydrogen is applicable in combustion engines, synthetic fuels, ammonia generation, and long-term energy storage. These properties make hydrogen a pillar of the new energy system, especially in hard-to-electrify industries or those that are inefficient to electrify directly. But it is not the element hydrogen itself that defines its sustainability and environmental friendliness, since hydrogen does not occur naturally in its pure form, but rather how it is produced. Currently, most of the world's hydrogen comes into being based on fossil sources, mainly natural gas, in the form of so-called steam methane reforming (SMR) [4]. This type of hydrogen is referred to as grey hydrogen, and it results in high carbon dioxide emissions, thus offsetting the green advantages of hydrogen consumption. Another form, blue hydrogen, applies the same method with the addition of storing and capturing (CCS) the emissions of CO_2. Although blue hydrogen is much cleaner than grey, it is indirectly linked to fossil fuel resources and infrastructure [5]. By comparison, green hydrogen is produced in an electrolysis of water process, as done through renewable electric power, e.g., solar power or wind energy [6]. There are no greenhouse gases produced in this process, and so indeed green hydrogen is a clean, sustainable solution, which can meet the decarbonization targets set globally [7]. Green hydrogen has gained importance as the urgency of climate change mitigation and energy transition policies has risen [8]. Countries globally, and particularly those bound toward net-zero goals, are rushing to invest in green hydrogen technologies in an attempt to decarbonise heavy industry, including steelmaking, cement production, and petrochemical refining, which is presently dependent on carbon-intensive fuels. Green hydrogen also has potential solutions to sectors that are difficult to electrify, including long-haul trucking, maritime shipping, and aviation, either as a foundation for synthetic fuels or direct propulsion [9]. Furthermore, green hydrogen is a possibility of balancing the electricity grids, where hydrogen can be used to fill the peaks and valleys of the supply and demand world, since it is a material through which the surplus electricity generated when nobody needs electricity can be stored and the release of then same can be released when everybody wants electricity. Such features not only assist environmental ambitions but also improve energy security and provide economic potential by establishing new hydrogen-based industries.

Nevertheless, the prospect of green hydrogen production is threatened by several technological and economic issues [10, 11]. Electrolysis is the primary technology of green hydrogen production, which consists of the disintegration of water (H_2O) into hydrogen (H_2) and oxygen (O_2) through electric energy. The most common types of electrolysers in use are alkaline electrolysers, proton exchange membrane (PEM) electrolysers, and solid oxide electrolysers (SOECs). The most developed and widespread technology is alkaline electrolysers, which are considered economical and scale well [12]. PEM electrolysers are more costly but more efficient, have a faster response time, and can be integrated more easily with variable renewable energy sources. SOECs work at high temperatures and promise perhaps even higher efficiencies, although they are still early in commercialisation [13, 14]. In addition to these, scientists are working on better materials, catalysts, and system architectures that will enhance performance, reduce cost, and increase durability. Moreover, there are moves to combine green hydrogen production with decentralised renewable energy generation, including solar farms and offshore wind platforms, to make self-sufficient hydrogen production modules.

This chapter explains the hydrogen classification by production means, with the differences between grey, blue, turquoise, and green hydrogen being noted. Particular interest is devoted to green hydrogen because it can contribute to achieving sustainability and decarbonization goals. Further, the article addresses technological approaches to green hydrogen production, compares the merits and drawbacks of all processes, and elaborates on their applicability in industry. With the world of energy rapidly changing, it is important to realise the various types and the mechanisms that facilitate green hydrogen production. In this discussion, the chapter tries to provide insight into why hydrogen is a vital element in ensuring a faster switch to a cleaner, more flexible, and future-ready energy system.

1.2. Hydrogen Production

Fossil hydrocarbons are catalytically cracked under steam (H_2O) conditions at 700-900 ^{0}C and 3-35 bar pressure to produce hydrogen (H_2) and carbon monoxide (CO) [15]. The most widely used heterogeneous catalysts are nickel (Ni), precious metals alloy like Ni/Al_2O_3 or Ru/ZrO_2 [16, 17]. As a hydrocarbon feedstock, natural gas is frequently utilised on an industrial scale. The main substance of natural gas is Methane (CH_4) with its molar fraction of 75.99 per cent. This is why this process is commonly known as steam methane reforming (SMR). Besides methane, natural gas also contains, in variable amounts, higher alkanes (ethane, propane, butane), inert gases (nitrogen, helium), and early so-called sour gases (carbon dioxide, the main, and hydrogen sulfide). Especially harmful is hydrogen sulfide (H_2S) included in the feed to downstream processes, because sulfur compounds poison catalysts, chemisorbing on the metal centers of the active surface area of catalysts [18]. As such, H_2S ought to be removed during the hydrocarbon feed. H_2S is normally eliminated during hydrotreating or absorption on activated zinc oxide [19]. The feed is then subjected to proper pre-treatment, and the steam reforming stage is then activated. The overall hydrocarbon conversion and the methane conversion in specific terms are captured by the chemical equations given in Eqs. 1 & 2, respectively. The reaction is very exothermic and will, thus, need great access to an external heat source. The heat is added to the system as steam and/or by heating the reactor externally. Natural gas and off-gases during hydrogen purification are common fuels. Moreover, the exothermic water-gas shift (WGS) reaction (Eq. 3), whose heat can be combined with the next stage of the chain of SMR.

$$C_nH_m + n\ H_2O \rightleftarrows n\ CO + (n + m/2)\ H_2 \quad (1)$$

$$CH_4 + H_2O \rightleftarrows CO + 3\ H_2\ \Delta H^0{}_R = +206.3\ kJ/mol \quad (2)$$

$$CO + H_2O \rightleftarrows CO_2 + H_2\ \Delta H^0{}_R = -41.2\ kJ/mol \quad (3)$$

High temperatures, low pressures as applied using Le Chatelier's principle, and the addition of extra steam help to improve the SMR performance in an attempt to avoid the formation of coke. The latter is represented in the ratio between steam and carbon. Common ratios are 2-5, and 2.5-3.5 ratios have often been cited as an optimal ratio of purified H_2 yield, efficiency, and plant size. Future development of SMR specifically aims at improving energy efficiency of steam pre-heating with Low intensity of fuel consumption and higher outlet temperature of the reformer. SMR is a mature and well-developed technology (TRL 9) [20, 21]. The largest ones have a capacity of up to 120,000 Nm^3/h H_2 production and downstream produce ammonia (NH_3). SMR of higher heating value (HHV) has a total process efficiency of between 65-70 percent [22, 23].

1.2.1. By-product steam

The steam, which is the overflow heat in the convective section of flue gas and the partial cooling of the product stream, can be sold to supply steam to the adjacent industrial plants or air in steam turbines. On an HHV basis, the estimated limit of process efficiency of SMR based on the practical process is 88.9 - 90.7%.

1.2.2. Carbon capture and storage-based steam methane reforming

There are indicators that carbon capture and storage (CCS) technologies can be used to restrain process-related CO_2 emissions and provide the production of low-CO_2 hydrogen. The process of production and the resources of fossils used by SMR-CCS are entirely the same as those used by grey H_2, hence the name SMR-CCS. The resulting part of CO_2 is mostly captured and stored in geological sites instead of being released into the atmosphere. Because most of the direct CO_2 emissions are avoided in this manner, H_2 made with SMR-CCS is occasionally described as low-CO_2 or blue H_2, though never when the captured CO_2 is not stored.

1.2.3. Methane pyrolysis

In methane pyrolysis (MP), the so-called methane decomposition and methane cracking, CH_4 is decomposed (cracked) to release gaseous H_2 and elemental carbon (C).

$$CH_4 \rightleftarrows 2\ H_2 + C \quad \Delta H^0{}_R = +74.9 \text{ kJ/ mol} \tag{4}$$

Just like the SMR, in this case, too large amounts of CH_4, which is produced predominantly in the form of natural gas and, hence, is a fossil-fuel hydrocarbon source, are used. Even more CH_4 volumes are required to generate hydrogen utilising MP, with the consideration that the H_2/CH_4 molar ratio is 2:1 as compared to 4:1 in SMR. The CO_2 emissions are, however, not directly caused by MP. Therefore, H_2 derived by MP is occasionally termed as CO_2-free or turquoise H_2. It has been reasoned as having the potential of becoming a bridging technology to the climate-friendly production of hydrogen when using MP.

1.2.4. Natural gas as a feedstock

The industrial application of MP first applies to natural gas. Eventually, methane generated by the biogas plant can also be utilised. A limited number of studies have, however, been associated with the effect posed by the trace components in the feed gas on the key process variables such as the selectivity, the product quality, and the conversion. Nickel and iron-based Catalysts get more deactivated the more they are exposed to H_2S. Low concentrations of higher alkanes may have no negative, or indeed, a positive effect on CH_4 conversion, and their minimisation can reduce carbon catalyst deactivation. The removal of contaminants such as N_2 is important during natural gas processing[24], as components other than CH_4 may react to form undesirable byproducts, including saturated and unsaturated hydrocarbons, as well as polycyclic aromatic compounds. Hence product hydrogen stream may need to be purified, in cases where the hydrogen is to be utilised in sensitive processes, e.g., utilisation in fuel cells and in the chemical industry as a feedstock.

1.3. Types of Hydrogen

Hydrogen, in its end-use form, is chemically identical, but varies greatly concerning environmental impact, based on the method of production [25]. To simplify these distinctions, hydrogen is often categorised using colour codes which indicate its route of production and the carbon footprint it has. The significant forms of hydrogen are grey, blue, and green hydrogen, and the other upcoming classes are turquoise, pink, yellow, and white hydrogen. Each of these types is marked with different technological, economic, and ecological features.

1.3.1. Blue Hydrogen

Blue hydrogen is a low-carbon hydrogen produced through natural gas via steam methane reforming (SMR) or autothermal reforming (ATR) process, with the carbon capture, utilisation, and storage (CCUS) operation [26]. Here, the hydrogen is taken out of methane, and the carbon dioxide produced is stored and captured underground or utilised in industries, thus it does not escape into the atmosphere. Although blue hydrogen is much better at minimising greenhouse gas emissions compared to grey hydrogen, it is not zero-emission, since carbon capture systems are not perfect, and methane may leak during natural gas production and transportation. Blue hydrogen is occasionally viewed as a stopgap, a means of gradually scaling down the fossil-based production of hydrogen we have now to the widespread usage of green hydrogen, which is made using renewable energy sources in the future.

The carbon dioxide byproduct is never associated with the manufacture of hydrogen by the use of fossil fuels. The carbon footprint of the fossil-based hydrogen production is very sensitive to the kind of feed used as well as the technology used in the production [27]. The future of the blue hydrogen market is also predetermined by the prices of the fossil fuels, the nature of the global energy system, and the regulations on carbon emissions [28]. Traditionally, the most widely used feedstock in the production of hydrogen was natural gas and liquid petroleum. All that, however, was altered with the increase in the production of natural gas and the increased demand for transportation fuels in the past 30 years, and both hydrogen and syngas production shifted to natural gas and coal, with the use of liquid petroleum as a hydrogen feedstock much lower in the ranking chart. Blue hydrogen is generated using fossil fuels, mainly natural gas, by using reactions like steam methane reforming (SMR) or autothermal reforming (ATR), and it has carbon capture and storage (CCS) to limit the carbon emissions released during hydrogen production significantly. In steam methane reforming, reforming of methane takes place in the presence of steam at elevated temperatures to yield hydrogen and carbon dioxide. With blue hydrogen, the CO_2 by-product is captured and either stored in underground geological structures or reused in industry, rather than being emitted to the atmosphere [29, 30]. This results in blue hydrogen being a low-carbon alternative to grey hydrogen, which takes the same production route but releases CO_2 directly. However, blue hydrogen is not carbon-free. CCS systems have varying efficiency, and some percentage of carbon emissions could still be released to the environment. Moreover, natural gas extraction, processing, and transportation may lead to methane leakages, which is a highly efficient greenhouse gas and causes serious problems with climate change. Such aspects have prompted the discussion of whether blue hydrogen is environmentally beneficial at all. Nevertheless, blue hydrogen is frequently regarded as a practical and transitional method of cutting emissions in the short-term to medium-term. It also utilizes the existing natural gas infrastructure and enables the scale deployment of hydrogen to be rolled out as green hydrogen technologies are still maturing. In nations possessing large quantities of fossil fuels and CCS potential, blue hydrogen provides a means to start decarbonising energy systems without having to await the large-scale availability of renewable-based options. In this respect, blue hydrogen can be considered a bridge technology, allowing a slow transition to a cleaner energy system, with the path being open to the scale-up of green hydrogen, produced by electrolysis with renewable energy, with zero direct emissions.

1.3.2. Green Hydrogen

Internally produced green hydrogen is the product of electrolysis, or the ability of energy in the form of electricity to split the water (H_2O) into hydrogen (H_2) and oxygen (O_2) [31, 32]. When such electricity is generated purely using renewable power resources solar power and wind, then the resulting hydrogen is said to be green since no greenhouse gases are emitted in the process. Electricity is generated in solar panels or wind turbines, and this electricity is used to operate an electrolyser, which is a device where the water-splitting reaction occurs. The process results in zero direct emissions of hydrogen as an energy carrier, which is truly clean. Production of hydrogen by wind and solar is particularly appealing since these renewable resources are plentiful, sustainable, and rapidly becoming cost-competitive. With the ever-increasing solar and wind power capacity in the world, the combination of these energy sources with electrolysers makes decentralised and scalable green hydrogen production possible. This form of hydrogen will play an important role in the decarbonisation of those sectors that are challenging to electrify (heavy industry, aviation, long-range transport) and offering a renewable way of energy storage of any excess renewable electricity and the balancing of power grids.

Two significant components make up the green hydrogen system: the renewable energy source and the water electrolyser. The basic equation of water decomposition is given:

$$H_2O \text{ (Liquid)} + \text{Energy} = H_2 \text{ (g)} + \tfrac{1}{2} O_2 \text{ (g)} \quad (5)$$

Electrical energy makes use of a DC power source. The water electrolysis technology can be divided into three categories based on the nature of the electrolyte used in the cells: Liquid electrolyte: alkaline water electrolyser, alkaline anion exchange membrane. Acid ionomer: proton exchange membrane electrolyser and solid polymer electrolyser, in which electrolysis takes place. High temperature steam electrolyser and solid oxide electrolyser (Steam electrolysis), high temperature steam electrolyser and solid oxide electrolyser (HTSE and SOE) [33].

The PEM (Proton Exchange Membrane) contains electrodes and electrolytes, and the materials that have been used as the electrodes are platinum, iridium, and ruthenium. A small design and a high conductivity of the protons and high pressure (15 to 30 bar at 50 to 90 °C) denote the PEM [34]. The advantages of the PEM are associated with its rapid response rate and that it produces high-purity hydrogen (99.999 percent). Its disadvantage, however, is that it is very expensive since noble material is used in the electrolysis.

The AWE (Alkaline Water Electrolyser) is an electrolyser that is comprised of a diaphragm and two electrodes immersed in a silver-coloured electrolyte water solution that typically contains almost 40 percent of sodium hydroxide (NaOH) or potassium hydroxide (KOH) [35, 36]. The diaphragm that divides the two electrodes in the solution enables the flow of water molecules and the hydroxide ions and separates the H_2 and O_2 due to the aspects of safety and purity concerns. Hydrogen produced has a purity of 99.5 to 99.9 per cent, which can further be up to 99.99 per cent through the application of catalytic purification of gases. Performance of this type of electrolysis is influenced by the diaphragm, the type of anode and cathode material, and the thickness. The features of AWE and the PEM apply here in that AWE utilises a volatile liquid electrolyte, whereas the PEM utilises a solid polymer membrane electrolyte.

The AEM (Alkaline Anion Exchange Membrane) is assumed to be an amalgamation of the PEM and the AWE [37]. AEM is the conglomeration of the PEM and the AWE strengths. In such a way, the AEM operates at a low concentration alkaline solution rather than a 20-40% KOH or NaOH aqueous solution and solid electrolyte (polymeric) membrane. An anode in AEM is Ni-based (e.g., Ni foams), and the cathode has Ni, Ni-Fe, and $NiFe_2O_4$.

HTSE (High-Temperature Steam Electrolyser) refers to a high-temperature electrolyser, using steam [33]. The primary strength of this technology is that the disengagement of steam will use less amount of energy when compared to liquid water. The HTSE needs heat, as opposed to electric energy, to crack the water molecule. That is how it may be suggested to increase the efficiency of this process and reduce the cost of hydrogen manufacture.

Higher temperature is used in the SOE (Solid Oxide Electrolyser), and due to the low temperature of electrolysis, the electricity required to power its electrolysis is very little [14]. There is therefore an increase in the efficiency of the system since it makes use of low-cost thermal energy. The steam side on the cathode end of the hydrogen production unit of the SOE is subject to reduction to the hydrogen gas after the cathode reaction process, and subsequently, the oxide anions that are thus formed present the route in which the solid electrolytes combine to form the production of oxygen on the anode end.

1.3.3. Pink hydrogen

Pink hydrogen is a hydrogen production pathway that does not generate CO_2 directly [38]. Unlike green hydrogen, pink hydrogen is obtained as a result of electrolysis of water, and in contrast to the former, due to the assistance of electricity produced at nuclear power plants (NPP) [39]. Several advantages are associated with this move. Firstly, nuclear power is environmentally friendly in relation to other power sources. A nuclear energy global warming potential (GWP) is 0.027 kg CO_2 eq./kWh, and it is lower compared to that of natural gas, coal, oil, and renewable energy. Second, renewable energy costs more as compared to nuclear electricity. The weighted average levelized cost of energy (LCOE) of PV, onshore wind, and offshore wind was in 2021, reported by the International Renewable Energy Agency (IRENA) to be 0.048 $/kWh, 0.033 $/kWh, and 0.075 $kWh, respectively. The nuclear energy calculated LCOE was within the 0.015 $/kWh to 0.049 $/kWh range of reactors and countries, and its values were at par and even lower than the numbers of the renewable energy sources [40]. So, pink Hydrogen can be at least as cost-effective as green hydrogen and more so. Finally, it permits a constant and smooth provision of power. Typical hydrogen production technologies using pink electrolysis stand out as alkaline electrolysis (AEL), polymer exchange membrane electrolysis (PEMEL), and SOEC. Among them, SOECs show the highest-reported efficiency (81-86 %HHV) and are still not commercialized; they also can operate at elevated temperatures (600-1,000 °C) and thereby can recover waste heat. SOECs, however, are incapable of operating at their best during transient operation processes, as well as exhibiting low durability. In addition, electric heaters (EH) required in the process of producing high-temperature steam consume much power, resulting in a high cost of power. Therefore, serious research has been conducted to integrate SOEC with other processes to reduce power consumption.

1.3.4. Turquoise hydrogen

Compared to other means of producing hydrogen, turquoise hydrogen is one of the prospective green hydrogen production methods [41]. It is the endothermic pyrolysis of methane, and it needs lots of external sources of heat. Conventionally, pressure swing adsorption (PSA) purge gas is burned to provide this heat, which, however, introduces CO_2 emissions to the process [42]. Hence, the key to ensuring that turquoise hydrogen remains green is by ensuring the capture of the CO_2 emitted upon combustion. In this regard, oxy-fuel combustion has been considered as one of the technically feasible solutions, since it is thermally efficient and capable of capturing CO_2 effectively. It, however, requires a high-purity oxygen supply, which can only be produced at present by cryogenic air separation units (ASUs). Although they are reliable, ASUs are energy-consuming and lower the efficiency of the whole system, particularly when used with CO_2 compression and purification units (CPUs). Such demands induce economic challenges that will need to be solved with innovation or a combination with low-cost renewable power to realise a genuinely sustainable and commercially attractive route in the future hydrogen economy of 2025.

The most promising opportunity among the different technologies that exclude green and grey hydrogen is called turquoise hydrogen. It is produced through the pyrolysis of natural gas, and solid carbon is produced as a by-product. The Turquoise hydrogen possesses some advantages over other hydrogen production pathways. To begin with, the pyrolysis process is one step that does not require steam or even half of the feedstock required by the steam methane reforming (SMR). At room temperature, the enthalpy change of reaction per mole of hydrogen is 37.4 kJ/mol during the pyrolysis process, as compared to the results of SMR (41.3 kJ/mol) and the electrolysis value (285.83 kJ/mol) [43, 44]. It implies that turquoise hydrogen has an energy preference over the other hydrogen production pathways. Second, hydrogen of turquoise colour is environmentally friendly. The carbon of the natural gas is not released as CO_2, as is the case with the conventional pathways in the production of hydrogen. It is instead converted into solid carbon, thus there are no direct emissions of CO_2, but the energy used is also low, and there is no CO_2 emission. Monolith, the only global company to produce turquoise hydrogen, has the opportunity to reduce GHG by approximately 1 million tons compared to the conventional methods of manufacturing carbon black. Finally, economic viability can further be boosted by selling solid carbon, which will result as a by-product. Solid carbon may be produced in various forms, depending upon the catalysts and the operating conditions, as an amorphous form, carbon black, or nanofibers.

Black hydrogen is hydrogen gas, which is generated with coal, particularly bituminous coal or lignite (brown coal) as the main raw material [45]. It is produced by a chemical process called coal gasification, in which coal is heated to very high temperatures, usually between 1,200 °C and 1,500 °C, in a controlled atmosphere with little oxygen and steam. In this situation, the coal is broken down into a gas mixture called synthesis gas (syngas) that primarily consists of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), and trace methane and other gases. The syngas is then further processed (using more chemical reactions and purification steps) to remove the hydrogen, e.g., the water-gas shift reaction converts CO and water into more hydrogen and CO_2. Although this is a way to mass-produce hydrogen, it is ranked as one of the uncleanest and least sustainable ways to do it. Black hydrogen has a great environmental effect. Each kilogram of hydrogen generated through coal yields an estimated 15 to 19 kilograms of atmospheric carbon dioxide emissions. Such an enormous carbon footprint turns black hydrogen into a major cause of climate change and air pollution. Besides, other harmful by-products are also generated during the process, including sulfur compounds, tar, heavy metals, and ash, which have to be well handled and treated to avoid contamination of soil and water. Most often, the coal gasification process does not have adequate carbon capture and storage (CCS) mechanisms, and this implies that the bulk of the CO_2 emissions are pumped directly into the atmosphere.

1.3.5. Black hydrogen

Despite these disadvantages, black hydrogen is still manufactured in several countries because of the cheap availability of coal. Countries like China, India, and South Africa are dependent on coal as a source of energy and industrial operation, and consequently, black hydrogen is largely preferred due to economic viability. It is mostly utilized in the production of ammonia (in fertilizers), methanol, petroleum refinery, and in the generation of electricity. Those economic benefits, however, are achieved at the cost of environmental sustainability, national health, and global climate commitments. With the world more interested in carbon emissions and climate change, black hydrogen is slowly being used as a technology of yesterday, and that is unsustainable. Conversely, more modern and clean methods of hydrogen production are being supported as long-term solutions in a low-carbon future: blue hydrogen (natural gas produced with carbon capture) and green hydrogen (water produced using renewable electricity). These ways are in contrast to black hydrogen, which has high or no prospect of low or zero emissions and hence are more aligned with national and international net-zero targets. Overall, black hydrogen is the carbon-intensive mode of hydrogen production, namely, coal-based economies [46]. Although it can bring short-term economic gains to coal-rich areas, it has enormous environmental and health costs. With the world shifting towards cleaner energy systems, it is anticipated that the production and utilisation of black hydrogen will decrease, making way for sustainable and renewable hydrogen technologies, which are in line with the global trend of decarbonization. Different types of hydrogen, based on production methods and energy sources, from fossil-based, are given in the following Figure 1.

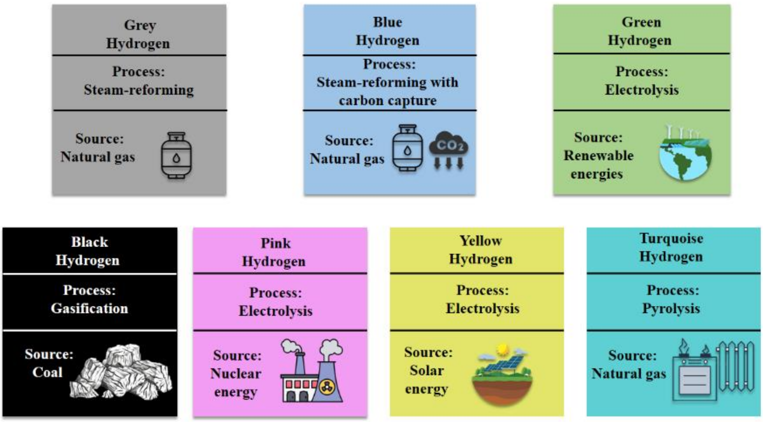

Figure 1: *Different types of hydrogen based on production methods and energy sources, from fossil-based (grey, blue, black) to renewable-powered (green, yellow, pink) and emerging methods like turquoise hydrogen.*

1.4. Methods of Green Hydrogen Production

1.4.1. Electrolysis process

Electrolysis is the technique of using electricity to separate water molecules to produce hydrogen and oxygen.

$$H_2O + Electricity \rightarrow H_2 + 0.5O_2 \tag{6}$$

Electrolysis of water is an old technology that has served in many industries for over a hundred years. The process of splitting water and hydrogen by water electrolysis using electrical energy. The amount of energy needed to generate hydrogen grows to a certain degree as the electricity needed in the process reduces with an increase in temperature. It is, however, more crucial due to the fact that the majority of power generated on this planet is achieved at very low efficiency through fossil fuels. It is now viewed as a significant process that can be implemented to generate high-purity hydrogen with the use of both water and renewable energy. Shortly, a larger role is foreseen for water electrolysers in decentralised hydrogen production, e.g., at hydrogen refuelling stations. As Figure 2 shows that electrolysis, a strategic approach that has been developed and portrays relevance, is the best method through which water can be split. It also involves the production of hydrogen through a reaction of any of the above substances with water. Proton exchange membrane, alkaline, and solid oxide electrolysis cells are used to perform electrolysis. Water might easily be split into hydroxide particles and hydrogen at the cathode end in solid oxide electrolysis cells and under alkaline conditions. On the anode end, the hydroxide particles are changed to O_2. The electrolyser that is recommended is called the solid oxide electrolysis cells, which use less electricity due to the increase in temperature in the intermediate cycles. With regard to the overall production and consumption of electricity, this warming causes improved electrolysis.

1.4.2. Solar-powered electrolysis

Solar-powered electrolysis Solar-powered electrolysis is a clean technology, which entails the electrochemical separation of water into hydrogen and oxygen utilising electric energy obtained from solar power. The sunlight is normally converted into electrical energy by photovoltaic solar panels, and this energy is used to power an electrolyser, usually a proton exchange membrane (PEM) model, which is highly efficient and quick to respond to changes in power input. The above systems lack efficiency due to the average efficiency of the solar panels (18-22%) as well as the energy efficiency of the electrolyser (60-80%). During the peak sunlight, a 1 kW solar system can produce approximately 0.076 kilograms of hydrogen daily, and this adds to approximately 27.7 kilograms a year in propitious circumstances. This method of green hydrogen generation significantly reduces the level of CO_2 pollution as compared to the conventional fossil-fuel-driven method of producing hydrogen. However, due to the fact that the level of solar energy does not always remain the same throughout the day, hydrogen production also fluctuates, and that is why energy storage, or a hybrid system, is needed to provide a constant supply of it. To conclude, the solar-powered electrolysis of water is a potentially successful line of clean hydrogen production, as the world is on the verge of shifting to renewable energy and decarbonization.

1.4.3. Green hydrogen production method

The solar-powered electrolysis method entails the use of solar energy to produce the electricity required to accomplish the electrolysis of water. Firstly, PV solar panels absorb sunlight and turn it into direct current (DC) power. This power is next delivered to an electrolyser, most usually a proton exchange membrane (PEM) or alkaline electrolyser, in which water molecules are broken into hydrogen and oxygen gases. In the electrolyser, an electric current is induced to flow through the water, and this causes the hydrogen to be separated towards the cathode, where the hydrogen ion obtains electrons to form hydrogen gas; the oxygen will be set free at the anode. It is an extremely controlled operation, as efficient as possible, and tends to come with power management systems in order to handle the on-demand power production of the sun, based on the strength of the sun's rays. Hydrogen gas so produced can be captured, stored, and utilised as a clean source of energy. This technique allows renewable, carbon-free production of hydrogen by the direct combination of solar electricity and water electrolysis.

1.4.4. Wind-powered electrolysis

Wind-powered electrolysis is a technique to harness wind power and apply it to electrolysis of water, using the electricity generated to separate water into hydrogen and oxygen. Wind turbines in this process extract the kinetic energy of the wind and turn it into electrical energy, typically alternating current (AC). This electricity may be used directly or may be modified to the form of direct current (DC) to power an electrolyser, e.g., a proton exchange membrane (PEM) or alkaline electrolyser. In an electrolyser, the electricity flows through it, in which the water molecules (H_2O) are split into hydrogen gas at the cathode and oxygen gas at the anode. The generated hydrogen can be captured, stored, and utilised as a clean fuel in diverse activities, such as transportation, industry processes, and electric power production. Wind-powered electrolysis provides a renewable and green alternative to produce green hydrogen since wind energy is renewable and has no greenhouse gas emissions. However, due to the variable wind speed, storage of energy or connection to the grid is frequently considered to stabilise the production of hydrogen.

1.4.5. Biological methods

Biological hydrogen production is a category of renewable processes, whereby living organisms, primarily microorganisms such as bacteria, algae, and cyanobacteria, are used to produce hydrogen gas (H_2) as a by-product of their natural metabolic processes. These biological systems depend on enzymes like hydrogenase and nitrogenase that facilitate the generation of hydrogen according to the environmental setting. The exceptional benefit of this strategy is that it can use low-value resources, including agricultural waste, wastewater, and sunlight, to create hydrogen in a carbon-neutral or even carbon-negative way. This renders it extremely viable in terms of sustainability compared to the conventional approaches, such as steam methane reforming, that release large volumes of CO_2. Biological hydrogen production can be seen within the context of the whole biohydrogen technology, which is a sub-discipline of green energy technology that is focused on creating inherently clean, decentralised, and low-cost sources of hydrogen, particularly applicable to rural or resource-constrained regions. Although in the early phases of industrial application, the technology is becoming interesting owing to its environmental advantage, and the current drive towards clean hydrogen economies across the world.

1.4.6. Thermochemical method for green hydrogen production

Thermochemical processes involve the production of hydrogen by driving high-temperature chemical reactions with heat typically supplied using renewable resources such as concentrated solar power, geothermal energy, or the combustion of biomass. They are usually done by decomposing water or other compounds that contain hydrogen using heat reactions without the use of electricity. As an example, in thermochemical water splitting cycles, heat is used to continuously promote a sequence of chemical processes that eventually split water into hydrogen and oxygen. Thermochemical methods hold potential to be a low-greenhouse-gas-emission route to clean, sustainable hydrogen, with the key distinction of using renewable heat as a feedstock rather than fossil fuels. Most of these technologies are, however, still under development and need special materials and temperature control to be effective.

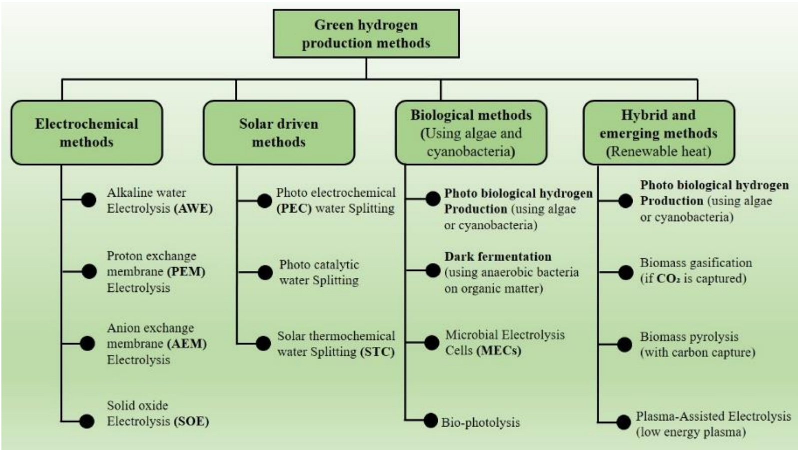

Figure 2: *A structured overview of green hydrogen production pathways, showcasing advanced electrochemical, solar-driven, biological, and hybrid technologies focused on sustainability and renewable energy integration.*

1.5. Challenges and Opportunities

1.5.1. Cost and Efficiency

Cost reduction and efficiency are one of the largest obstacles in hydrogen production and green hydrogen in particular. As of 2022, green hydrogen generated through electrolysis has a cost of between 4 to 6 US dollars per kilogram, making it much more expensive than hydrogen generated by fossil fuels (about 1 to 2 US dollars per kilogram using steam methane reforming). To make hydrogen competitive, it is important to improve the efficiency of electrolysers, reduce the expense of renewable power, and develop catalyst and membrane materials. Research is expected to enhance electrolyser efficiencies to exceed 70 percent and cut capital costs in half by 2030. Figure 3 shows a modern Sankey diagram of the pathways of hydrogen production in 2025.

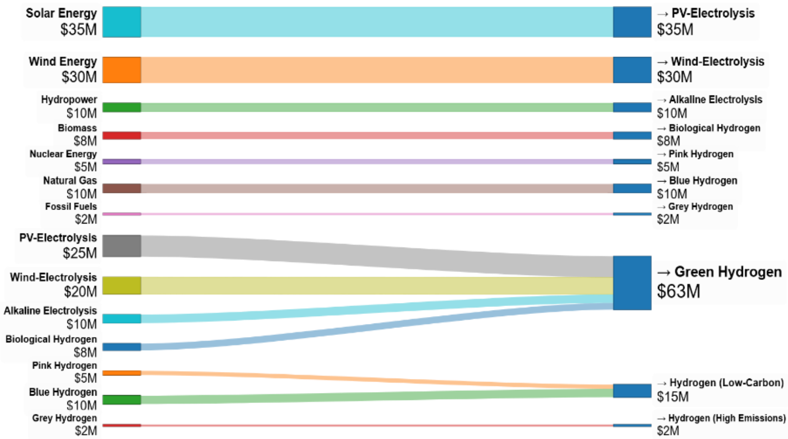

Figure 3: *Renewable and non-renewable sources of energy, through the main conversion processes, to the end uses of hydrogen in industry, transport and power*.

1.5.2. Scalability

The potential of green hydrogen to be produced on a large scale is enormous and can serve energy needs in the future. In order to provide an example, the International Energy Agency (IEA) suggests that global demand for hydrogen could extend to over 500 million tons by 2050, as opposed to the current requirement of 90 million tons in 2020. The opportunities include scaling up manufacturing capacity and facilities, integrating renewable energy sources, and scaling up large-capacity electrolyser plants. Most countries have revealed some ambitious goals, such as the European Union, which hopes to possess 40 GW of renewable hydrogen electrolysers by 2030.

1.5.3. Infrastructure

The challenges are of building an extensive hydrogen production, storage, as well as transportation infrastructure. Low energy density, low molecular size of hydrogen would also require special high-pressure tanks, pipes, and precautionary measures. At present, hydrogen infrastructure is not extensive, e.g., there are currently 500 hydrogen refuelling stations globally, predominantly in Japan, Europe, and California. The infrastructure will have to be expanded, which will need significant investments estimated in hundreds of billions of dollars worldwide over the next 20 years, to allow broad applications in industries, transport, and power generation. Figure 4 shows the low usage of low-emission hydrogen sources.

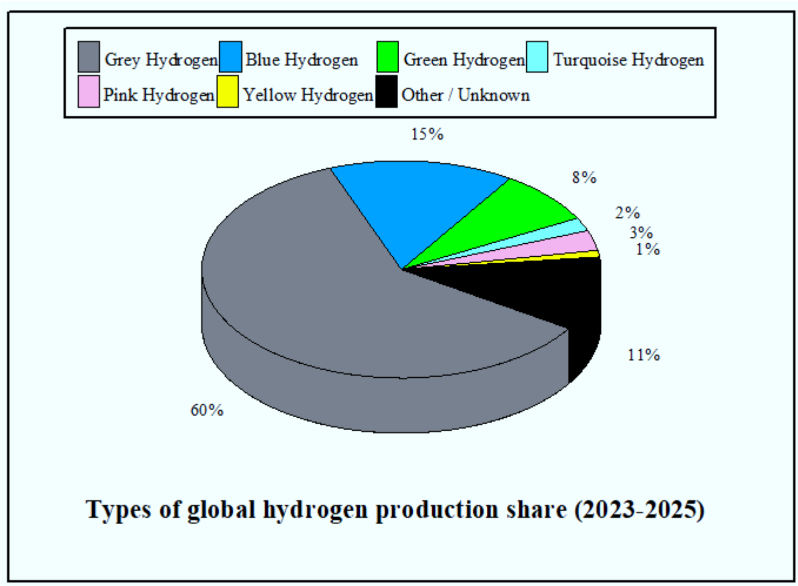

Figure 4: *Worldwide hydrogen capacity (2023-2025) is dominated by grey hydrogen (60%), followed by blue (15%), green (8%), and other colours such as pink, yellow, and turquoise.*

1.6. Conclusion

Hydrogen is a new, clean, and flexible energy carrier whose importance has been re-engineered by the ultimate transition to a low-carbon and sustainable energy future in the world. The contrast of hydrogen in various colours, namely, hydrogen grey, blue, turquoise, and green, defines the difference in the impact that the various production routes have on the environment. Green hydrogen that is produced using renewable sources of energy, including wind and solar, through the process of electrolysis, emerges as the most viable and eco-friendly option amongst the rest. It provides a zero-emission route to decarbonization of hard-to-electrify sectors, such as heavy industry, long-haul transportation, and grid energy storage. This potential fits right into the ambitions of the international climate policies and net-zero pledges. To sum up, green hydrogen has the potential to transform energy systems in the world, yet achieving this promise requires intense action in technology innovation, infrastructure building, and policy reinforcement. Research investments in improving the efficiency of electrolysers, dropping production costs, and increasing the scaling of renewable energy integration are essential. At the same time, global cooperation on standards, safety measures, and market structures will also be needed to realise the successful implementation of hydrogen technologies. With the world racing towards a decarbonised future, green hydrogen is expected to be at the centre of developing a clean, resilient, and inclusive energy landscape.

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CHAPTER TWO

INTRODUCTION TO HYDROGEN ECONOMY AND HYDROGEN AS A SUSTAINABLE ENERGY CARRIER

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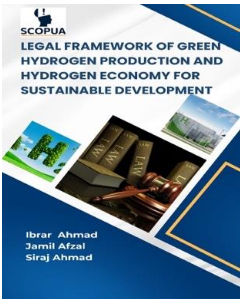

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Abstract

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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CHAPTER THREE

INTERNATIONAL AND COMPARATIVE LAW PERSPECTIVES OF HYDROGEN ECONOMY

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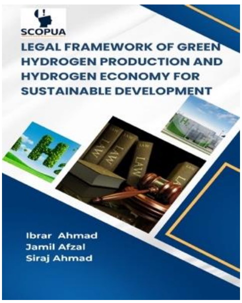

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Abstract

This chapter delivers a detailed analysis of the legal frameworks underpinning the global hydrogen economy, focusing in particular on international legal systems and comparative national strategies. This chapter commences by considering the functions of primary international legislative instruments, i.e., multilateral treaties and conventions, for the regulation of international hydrogen trade (cross-border movement of hydrogen) and the role they play in promoting international cooperation. Key agreements such as the United Nations Convention on Contracts for the International Sale of Goods (CISG) and WTO frameworks set the baseline rules for cross-border hydrogen deals, common rules on certification, trade, and compliance. These international legal frameworks are an essential way of facilitating the frictionless flow of hydrogen-related technologies and resources internationally, given the inherently cross-border aspects of hydrogen production and trade. The chapter then shifts to examining how different jurisdictions, including the EU, the US, and India, have formulated regulatory approaches to regulate hydrogen technologies. Through the analysis of the way national legal systems have transposed international standards to the domestic level, the chapter points out the varied regulatory solutions and the range of legal instruments that foster the development of hydrogen.

Keywords: *Perspectives of Hydrogen Economy; International and Comparative Law; Comparative Law of Hydrogen Economy; International Law of Hydrogen Economy*

3.1. International Law and the Hydrogen Economy

The Paris Agreement (2015), the United Nations Framework Convention on Climate Change (UNFCCC), and the Kyoto Protocol are important in the context of hydrogen at the global level [1]. These deals have paved the way for sector coupling and decarbonization, seeing hydrogen increasingly tipped as a key component in the global clean energy shift. The Paris Agreement, which serves as the bedrock of international climate architecture, seeks to cap global warming to well below 2°C but is pursuing efforts to limit the temperature rise to 1.5°C and calls for innovation in clean technology in areas like hydrogen [2],[3].

Although voluntary "Nationally Determined Contributions" (NDCs) underpin national pledges in the accord, there's no way to ensure compliance [4]. This non-obligatory approach entails that although countries are invited to include hydrogen in their climate strategies, they are not obliged to achieve any target related to hydrogen deployment. The consequence is that hydrogen policy often stands or falls based on (soft) law, not so much due to robust legal obligations.

The Kyoto Protocol set binding targets for the reduction of greenhouse gas emissions for developed countries and developed mechanisms for its implementation, including emissions trading (ET), joint implementation (JI), and the Clean Development Mechanism (CDM) [5],[6]. These measures created an incentive for low-carbon investments, including hydrogen technologies, especially in the developing world. However, the Kyoto Protocol was flawed, as it did not include emerging economies, which did not share similar binding targets. This void is even more striking now that emerging economies are gaining importance in the hydrogen transition. The lack of punitive or coercive tools has delivered serious challenges for holding to account those who do not fulfil commitments relating to hydrogen. This is particularly significant in developing countries, in which resources for hydrogen projects are scarce and national institutions are not able to adequately fulfil international obligations. When it comes to the future, it is evident that the treaties provide a globally broad framework for hydrogen implementation, while their success will rely on how countries implement these global commitments into tangible strategies at home.

The hydrogen economy and multilateral environmental agreements (MEAs), including the Convention on Biological Diversity (CBD) MEAs establish norms for environmental conservation that guide how new technologies, like hydrogen, may be introduced and deployed sustainably and in a way that does not undermine biodiversity [7],[8]. The CBD stresses the importance of a precautionary approach in large projects (like hydrogen production) to prevent possible damage to ecosystems and local populations. It is consistent with the main Sustainable Development Goals (SDGs), such as SDG 13 (climate action) and SDG 7 (affordable and clean energy). As a result, MEAs help bring the technological side of the development of hydrogen technologies together with respect for the environment while contributing to both climate mitigation and sustainability goals in general. Take the CBD, which encourages countries to undertake a thorough analysis of the ecological implications of hydrogen projects before advancing large-scale infrastructure. In the rapidly growing hydrogen economy, MEAs can be one of the institutions to ensure social and environmental considerations in national hydrogen policy. This is relevant for countries wanting to achieve climate goals, but be aware that their energy approaches are unintentionally deleterious to biodiversity or people.

3.2. International Trade Law and the Hydrogen Economy

International trade law, governed by agreements like those under the World Trade Organisation (WTO), plays a pivotal role in the development of the global hydrogen economy [9],[10]. The General Agreement on Tariffs and Trade (GATT), the Agreement on Subsidies and Countervailing Measures (ASCM), and the Technical Barriers to Trade (TBT) Agreement are essential in shaping the rules for hydrogen trade across borders. They support non-discrimination and transparency in trade, both of which are essential to allowing hydrogen to flow freely across the world. One of the mega-issues in the hydrogen trade is the influence of tariffs and non-tariff barriers, which can make the cost of hydrogen and its infrastructure rise, explaining why trade in hydrogen has remained relatively small compared to that of natural gas. The WTO's non-discrimination principle would mean that countries cannot take discriminatory measures against imported hydrogen technologies (including green hydrogen) unless they can justify them by invoking exceptions, such as to meet national security considerations. However, the WTO has yet to formulate rules specifically for hydrogen, and so a great deal will hinge on the interpretation and enforcement of these agreements about this new sector. Taking into account the hydrogen economy, international trade law will be even more important. Making it possible to access the market and ensure the security of investment will require aligning regulatory requirements to establish a common certification scheme and to deal with the legal issues involved in the cross-border transportation of hydrogen. The trade law will also have to respond to specific issues related to the hydrogen market to reconcile fair competition with security and environmental protection. As the hydrogen economy grows, so will policy frameworks have to respond to new needs, especially in developing countries. Two factors hamper the quick rollout of hydrogen technologies in these regions: legal uncertainty, policy fragmentation, and a lack of infrastructure. Supportive, non-discriminatory regulation and administration of standards could also be supplemented with improved enforcement mechanisms, more explicit provisions ensuring that investments in the area are protected, and internationally aligned action to promote the deployment of hydrogen technology at scale, productively, and sustainably.

3.3. Energy Role of International Organisations

3.3.1. International Energy Agency (IEA)

The International Energy Agency (IEA) has historically played a vital role in influencing global energy strategy, and the energy group's activities in the hydrogen space are no different [11]. The IEA is an advisory body with a brief to provide policy guidance, thorough analysis, and facilitate collaboration among member countries. Its major publications, like the Global Hydrogen Review or the future of Hydrogen, offer crucial analysis of how to scale up the production of hydrogen, lower costs, and then roll out the product across global energy systems. IEA's Hydrogen Roadmap Providing recommendations, in detail, for governments and industries, the IEA's Hydrogen Roadmap acts as a vital reference for any country working on or looking to develop a hydrogen strategy [12],[13]. The IEA's greatest strength is being able to offer solid analytical frameworks for the deployment of hydrogen. The agency also notes the need for upscaling low-emissions hydrogen production, notably electrolysis from renewable power and investment in electrolyser manufacturing capacity. The IEA has also championed the establishment of international certification schemes to guarantee the environmental soundness of hydrogen supply chains. For example, the IEA's work on ISO technical standards on greenhouse gas emissions accounting in hydrogen production is central to the development of emerging certification systems, including in the European Union, the United Kingdom, and Australia. However, the IEA's sway is limited by the fact that it does not have enforcement power. Although it can offer advice and promote collaboration, it is powerless to force sovereign states to follow its recommendations. As a neutral agency that relies on voluntary compliance, whether the OIE will succeed is largely in the hands of individual countries willing or not willing to adopt their policies to global best practices. Secondly, there are still strong economic hurdles to hydrogen deployment. The IEA calculates that hundreds of billions of dollars of investment are needed to expand the production of low-emission hydrogen to the levels required to meet global climate goals. The IEA's lack of mandate to promote investments in hydrogen infrastructure reflects the importance of complementary financial mechanisms, perhaps led by multilateral development banks or climate finance institutions [14],[15].

3.3.2. International Renewable Energy Agency (IRENA)

The International Renewable Energy Agency (IRENA) has become a leading champion of global hydrogen arrangements, which aim for policy harmonisation, capability development, and the establishment of a legal and regulatory framework supportive of the global hydrogen economy [16],[17]. IRENA's work that is particularly relevant in the context of accelerating cross-border trade in hydrogen is one that involves advocating harmonised certification schemes and sustainability criteria that can facilitate trade in hydrogen and its derivatives. The joint IRENA Collaborative Framework on Green Hydrogen has been critical in facilitating international collaboration [18]. Several countries, including Germany, Japan, Morocco, and the United Arab Emirates, have worked with IRENA to help ensure their domestic hydrogen strategies are benchmarked against global best practices. The National Hydrogen Roadmap of Morocco and Japan's strategy for importing green hydrogen, for example, mirrors IRENA's influence and its certification, emissions accounting, and infrastructure frameworks. This collaboration has led to case study agreements, pilot initiatives, and common technical standards, which provide a real indication of convergence in law. However, there are still challenges in the face of regulatory diversity. The European Union has established strict emission standards for green hydrogen, but the United States, among other countries, has looser benchmarks. Such inconsistencies hinder cross-border trade, forcing exporters to jump through legal hoops to access various markets. IRENA's advocacy for investments in public-private partnerships and attraction continues to support these initiatives to enable developing countries to engage with hydrogen economies.

3.3.3. World Trade Organisation (WTO)

The World Trade Organisation (WTO) assumes an important role in the development of the legal environment for international hydrogen trade, especially for market access, dispute settlement, and trade policy coordination between its member states [10],[19]. Key WTO agreements, such as the General Agreement on Tariffs and Trade (GATT) and the Agreement on Subsidies and Countervailing Measures (ASCM), are central mechanisms for the governance of hydrogen trade about export duties, the capacity to manage subsidies directly to hydrogen, and the intellectual property status of hydrogen production technologies. Since hydrogen is now becoming an independent product traded on the market, the importance of the WTO in bringing it into the market is growing. Some targeted trade barriers are already emerging, including plans to limit the export of hydrogen from domestically produced renewables. While these measures provided ambiguity as to whether export of hydrogen would be treated differently, they raised the risk of issues relating to supply security and market distortion and could place restrictions on hydrogen exporters. The WTO's dispute system could be a crucial tool for addressing disputes over these issues and helping ensure that national rules do not represent hidden trade barriers.

The WTO struggles to make its trade rules compatible with the particularities of hydrogen as it also crosses with environmental regimes. The multiplication of bilateral and regional agreements, with their own sets of norms, hampers the striving for coherence in hydrogen trade at a global level. Therefore, the WTO needs to cooperate closely with organisations like IRENA and IEA to ensure the complementarity of trade policies, mutual recognition of standards, and avoidance of regulatory fragmentation [20],[21].

While there may be agreement on the objective of creating open markets, regulatory coherence, and international cooperation, challenges persist between different legal systems and institutional preferences. Nonetheless, instances of successful cooperation, such as that of IRENA and WTO, do exist and indicate the possibility of synergies and a way forward. Such collaborations are the key to surmounting regulatory and legal obstacles that are standing in the way of bringing hydrogen technologies to scale.

3.4. Global Standards for Hydrogen Technologies and Safety

The development and use of international standards play a key role in the advancement of hydrogen technology and applications around the world [22]. The necessity of these standards, and especially of those established by the International Organisation for Standardisation (ISO) and the International Electrotechnical Commission (IEC), is, from a technical point of view, the basis for guaranteeing that hydrogen technologies are safe and can also be applied in different regions. Standards produced under the auspices of the ISO and IEC are essential to the development of international trade, investment, and operational interoperability by providing a core set of technical specifications and safety benchmarks for the production, storage, transport, and use of hydrogen. These harmonised standards fill these regulatory voids and ensure that hydrogen technologies can be deployed safely and in a uniform manner, irrespective of where the technology is introduced. They lower trade barriers, facilitate cross-border investment, bring clarity to manufacturers, operators, and regulatory authorities, and can help scale hydrogen technologies.

Central to the safe introduction of hydrogen as a fuel are formal international standards, including the ISO 14687 requirement for the quality of hydrogen fuel for fuel cell vehicles and the ISO

16110 for hydrogen generation system safety and performance [23],[24]. ISO 19880 also specifies design and functional requirements for hydrogen fuelling stations that are in place to ensure that the refuelling infrastructure operates safely and optimally [25],[26]. For fuel cell technologies, both for stationary and mobile applications, safety and performance are covered by the IEC 62282 standard, whereas the IEC 60079 series deals with the use of electrical apparatus in explosive atmospheres, which is crucial for hydrogen production and refuelling stations [27],[28]. More recently, ISO/TS 19870 was published as a technical specification to assess greenhouse gas emissions in the hydrogen value chain, which helps to foster transparency and test sustainability claims [29]. These standards are crucial to verifying the reliability, safety, and quality of hydrogen technologies, to stimulating worldwide acceptance of hydrogen technology, and to the infiltration of hydrogen into the international supply chain.

To promote safety through a transparent framework, the standards of ISO and IEC also facilitate the integration of hydrogen technologies into different markets by guaranteeing interoperability and equality. Standardisation facilitates the transfer of technology, saves costs, and de-risks investment by providing a predictable regulatory regime. It also promotes the trust of the public in hydrogen technologies by assuring that they comply with safety and quality criteria that are universally accepted. However, there are many complications to accomplish a reconciled safety rule across jurisdictions. National and regional variations still inhibit regulatory consolidation as differences in public safety priorities, environmental rules, and technological preparedness amongst member states persist. For example, Europe’s strict safety standards for hydrogen refuelling stations and production stations stand in stark contrast with relatively weak safety frameworks in some parts of Asia and Africa [30]. In addition to this, the use of more advanced safety solutions can be taken on quicker by the early movers of hydrogen technology, while poorer regions may slow down in terms of implementing best practices. These heterogeneous regulations, combined with differences in technology readiness, make it difficult for hydrogen technology to be scaled globally.

Work towards harmonising safety standards is ongoing, with substantial coordination at the international level, e.g., between ISO and IEC and organisations like the IRENA (International Renewable Energy Agency) and the IEA [31]. These companies, alongside local regulators and industry bodies, are collaborating to harmonise safety protocols and produce common guidelines. Some advances are being achieved at the European Union (EU) and Organisation for Economic Cooperation and Development (OECD) level, such as the development of common safety regimes to fill regulatory gaps [32]. Such partnerships are essential for the development of stable regulatory frameworks, the lowering of compliance costs, and facilitating an enhanced global deployment of hydrogen technologies. Despite the obstacles, this GLIH work is crucial to maintaining the safety, security, and accessibility of hydrogen, wherever it is used. Overall, the importance of following ISO and IEC along the pathway to global safety and interoperability in hydrogen technologies and systems is essential to ensure that hydrogen is adopted as a worldwide clean energy solution. They form the necessary base for technical requirements to ensure the safe use of hydrogen technologies and to facilitate international trade and investments. International collaboration and also proactive safety standard updates are necessary to respond to new challenges: new technologies, safety issues, and regional regulatory differences, due to the fact that hydrogen technologies are now evolving.

3.5. Comparative Law Analysis: Hydrogen Economy Regulations in Key Jurisdictions

3.5.1. European Union (EU) Hydrogen Legal Framework

The European Union (EU) Green Deal and EU Hydrogen Strategy, both published in 2020, are complements to the EU legal and policy structure for hydrogen within an energy policy framework [33],[34]. The Green Deal is an EU initiative under which the EU pledges to become climate-neutral by 2050, with hydrogen considered to be a key enabler to decarbonise hard-to-electrify sectors such as heavy industry, long-distance transport, and heating [35]. The EU Hydrogen Strategy is a logical next step following the EU's previous work on renewable hydrogen, which supplemented previous policies on conventional, synthetic, and low-carbon fuels, as well as the overarching objective of reducing emissions across every sector.

It focuses largely on legal measures, such as support for hydrogen infrastructure, standardisation of hydrogen technologies, and the establishment of clear regulatory frameworks that would allow cross-border trade and market integration, among other things. Its main features include ambitious objectives, such as the production of 10 million tonnes of renewable hydrogen by 2030 and the development of hydrogen valleys and hydrogen road transport in Europe [36],[37]. Policy measures such as the H_2 and Decarbonised Gases Market Package and delegated acts under the RED add layers to the definition of renewable hydrogen with strong criteria around life-cycle emissions and additionality - clear signals and a system of traceability for investors and the market. The EU approach is phased, with a first phase centred on the deployment of green hydrogen in existing industrial uses and pilot projects and latter phases targeting increased production, infrastructure development, and integration of hydrogen across energy systems. This staggered approach allows the legal and regulatory framework to develop alongside technological and market developments, and it is flexible as the hydrogen economy matures. It focuses largely on legal measures, such as support for hydrogen infrastructure, standardisation of hydrogen technologies, and the establishment of clear regulatory frameworks that would allow cross-border trade and market integration, among other things. Policy measures such as the H_2 and Decarbonised Gases Market Package and delegated acts under the RED add layers to the definition of renewable hydrogen with strong criteria around life-cycle emissions and additionality - clear signals and a system of traceability for investors and the market. The EU approach is phased, with a first phase centred on the deployment of green hydrogen in existing industrial uses and pilot projects and latter phases targeting increased production, infrastructure development, and integration of hydrogen across energy systems. This staggered approach allows the legal and regulatory framework to develop alongside technological and market developments, and it is flexible as the hydrogen economy matures.

***Funding Tools and EU Policies Supporting Hydrogen Development*:** The EU has developed a variety of funding options and policy tools to support research, innovation, and infrastructure in a bid to achieve its hydrogen aspirations [38]. At the top of the list is Horizon Europe, where a €1 billion budget is earmarked for the Clean Hydrogen Partnership in support of joint research activities and the establishment of hydrogen valleys across Europe [38]. One of the world's largest funding programs for low-carbon technologies, the Innovation Fund has already awarded billions of euros to hydrogen-related projects. The Connecting Europe Facility (CEF) equally stimulates EU hydrogen development by facilitating cross-border hydrogen infrastructure [39]. The most recent calls for proposals have earmarked €600 million for Projects of Common Interest (PCIs) or Projects of Mutual Interest (PMIs) to streamline permitting and regulatory processes for certain important hydrogen interconnections [39],[40]. Furthermore, member states are permitted to support hydrogen projects under the EU's State Aid Guidelines, so national hydrogen efforts can continue with respect to the EU legislation. Initiatives such as the Clean Hydrogen Partnership and other calls for proposals all support the continuous deployment of funds towards research, demonstration, and market uptake, further heralding the EU's commitment towards enabling a strong hydrogen economy.

The EU Emissions Trading Scheme (ETS) is a core pillar of the EU's climate policy and a key driver for the uptake of green hydrogen [41]. The ETS places a price on carbon emissions, creating economic penalties for carbon-intensive energy production and a corresponding advantage for switching to low-carbon and renewable hydrogen. The scheme has just been reformed to cover all hydrogen production pathways as well, which entails that renewable and low-carbon hydrogen plants have access to free allowances and market signals. The package known as Fit for 55, which lifts the level of ambition of the ETS and broadens the ETS, will pave the way for hydrogen uptake to go faster by making green hydrogen more economically competitive against fossil-based solutions. Introducing the Carbon Border Adjustment Mechanism (CBAM) will guarantee that hydrogen products imported into the single market are subject to the same environmental requirements, preventing carbon and environmental leakage and guaranteeing a level playing field for EU hydrogen producers [42],[43]. Combined, these steps support the EU's climate and energy leadership and boost investment in green hydrogen while keeping EU-produced hydrogen competitive internationally.

***Regulatory Authorities and Legal Background*:** Hydrogen energy policies in the EU. The regulation of hydrogen power exists in various institutions and actors in the EU, of which the European

Commission and its DG Energy are among the most significant actors [34],[44]. The Commission, in particular its Directorate-General for Energy, has the task of establishing and stimulating hydrogen-related legislative frameworks, to follow up on the progress, and to guarantee that it would be compliant with the EU-level energy and climate objectives. The European Court of Justice (ECJ) is also instrumental in interpreting and enforcing EU legislation, making sure that national hydrogen policies are in line with this legal framework, and settling issues on cross-border commercial hydrogen and market entry [45],[46].

The EU's hydrogen legal framework is a tangled labyrinth of rules, regulations, and decisions on everything from safety to the environment and market integration. The Hydrogen and Decarbonised Gas Market Package, which is in force from August 2024, foresees a Union-level certification system for low-carbon hydrogen, includes a requirement to unbundle hydrogen network operators, and lays down provisions on infrastructure planning, network tariffs, and third-party access [47]. These actions are in addition to implementing acts under the Renewable Energy Directive, which sets out criteria for renewable hydrogen and presents detailed life-cycle emissions calculation schemes. Other regulatory matters, such as the blending of hydrogen into natural gas infrastructure, the repurposing of existing infrastructure, as well as the setting up of hydrogen refuelling stations, are also covered by the EU legal framework, ensuring the safe and optimal integration of hydrogen in the energy system of the EU. The coherence and coordination between member states will be monitored by ACER and national regulatory authorities to foster the development of a homogeneous and competitive hydrogen market [40].

3.5.2. United States: Federal and State-Level Hydrogen Regulations

The regulation of hydrogen in the US is complex, involving many dimensions of interaction between federal states that play different but complementary roles in promoting the development of the hydrogen economy. Key federal agencies, such as the Department of Energy (DOE), the Environmental Protection Agency (EPA), and the Department of Transportation (DOT), are addressed, as well as the path-breaking actions of the states [48]. This analysis will also discuss the challenges of legal jurisdictional overlaps and regulatory fragmentation and the necessity of further harmonisation in the regulation of hydrogen. The federal role in hydrogen technology research, development, and demonstration (RD&D) is diverse and expanding and is a significant component of the RD&D investments that the federal government makes in advancements to energy technology. Among the most notable federal initiatives for the regulation and commercialisation of hydrogen technologies in the country are the Inflation Reduction Act (IRA), the Bipartisan Infrastructure Law (BIL), and the Energy Act of 2020 [49],[50].

***The Energy Act of 2020*:** The Energy Act 2020 was a game-changing piece of legislation offering a big, clear signal to accelerate the development of clean energy technologies, including hydrogen [51]. It provided nearly $2.5 billion in funding for Department of Energy (DOE) sustainable transportation activities, including designated funding for hydrogen and fuel cell R&D [52]. One of the Act's main goals was to promote innovation in hydrogen production, distribution, and storage, specifically, to help hydrogen develop into a commercially competitive alternative to the traditional fossil fuels. The Energy Act's funding applies in the context of a broader federal approach to make hydrogen a cornerstone of the U.S. clean energy future [53]. The fund does not just help to drive R&D in hydrogen technologies but also to create the infrastructure needed to enable widespread hydrogen adoption. The Act can deliver the latter, enabling the inclusion of hydrogen as an integral component of the overall energy scope in the country.

Bipartisan Infrastructure Law (BIL) and Inflation Reduction Act (IRA): In subsequent years after the Energy Act, the Bipartisan Infrastructure Law (BIL) and the Inflation Reduction Act (IRA) also ramped up the federal government's support of hydrogen [54],[55]. The BIL reserved $8 billion in funding for the establishment of Regional Clean Hydrogen Hubs (H_2Hubs), which seek to establish coordinated clusters of hydrogen producers, users, and infrastructure developers [56]. These hubs aim to help scale up the use of clean hydrogen by ensuring infrastructure for production and consumption is available in large enough quantities. The BIL also allocated $1 billion for clean hydrogen electrolysis technologies and $500 million for research, development, demonstration, and deployment (RDD&D) programs [49]. The IRA created a Hydrogen Production Tax Credit (PTC) that would incentivise the production of clean hydrogen [57]. These incentives, combined with funding to further develop clean vehicle manufacturing and to spur carbon capture, are spurring broad private sector interest in developing hydrogen production.

Department of Energy (DOE)**:** The DOE's Hydrogen and Fuel Cell Technologies Office (HFTO) is critical to the advancement of the hydrogen economy in the US [58]. The HFTO runs a number of funding programs for hydrogen R&D and deployment, including infrastructure grants, safety improvements, and permitting roadblocks [58]. While the 2023 Department of Energy $62 million grant was given to 20 projects in 15 states, it re-emphasises that the feds are deferring to states when it comes to unique hurdles relating to hydrogen [59]. One of the examples of that investment is the

Department of Energy's $1.66 billion loan guarantee for Plug Power, an innovative clean hydrogen production company. The loan will back hydrogen production plant construction, evidence of the level of federal investment in hydrogen infrastructure. The EPA is heavily involved in this aspect of the production of hydrogen to ensure that emissions standards are met by hydrogen production on a national level. Under the Clean Air Act, the EPA establishes emission standards for hydrogen production facilities that limit the greenhouse gases emitted by these operations to the greatest degree achievable. The agency's Clean Hydrogen Production Standard sets out the requirements for what qualifies as "clean" hydrogen, an important step to making sure hydrogen production can support the U.S.'s climate goals. In 2023, the EPA proposed a power plant rule that initially included substantial hydrogen blending in new natural gas-fired power plants. The rule was, however, significantly trimmed on concerns over cost and availability of hydrogen and infrastructure issues. Nonetheless, the continued regulatory work by the EPA signals an increasing awareness that hydrogen can help decarbonise hard-to-electrify sectors, like heavy industry and power generation. Another important subset of the regulatory portfolio of the EPA is that of safety regulations. The design, storage, and handling of hydrogen systems are covered by standards like NFPA 2 and NFPA 55, assuring that hydrogen infrastructure complies with the most stringent safeguards. The EPA's emissions and safety standards also help provide a stable regulatory environment for investment in hydrogen technologies.

The transportation of hydrogen, including through pipelines, is under the regulatory purview of the Department of Transportation (DOT) [60]. The U.S. Department of Transportation (DOT), through the Pipeline and Hazardous Materials Safety Administration (PHMSA), regulates the safety of hydrogen pipelines under 49 CFR Part 192 [60],[61]. Today, there are roughly 700 miles of hydrogen pipeline under federal jurisdiction, with more planned to go in the ground as hydrogen infrastructure grows. The PHMSA's efforts will focus on hydrogen pipeline integrity, material standards, and emergency response plans for accidents [62]. Recent research is primarily devoted to investigating the impact of hydrogen on pipeline materials and the development of standards for the safe transportation of hydrogen on a large scale. With increasing penetration of hydrogen, DOT's role in assuring safety and reliability for hydrogen transportation infrastructure will play a substantial role in the success of the hydrogen economy.

Although federal policies lay the groundwork for hydrogen commercialisation, the states are central to the promotion of hydrogen through state regulations and incentives. Several states, including California, New York, and Colorado, have also launched their own hydrogen regulatory initiatives, often with more aggressive plans to deploy hydrogen above what the federal government requires [53]. California has traditionally been an early adopter of clean energy policies, and in the case of hydrogen, its regulatory regime is reflective of its commitment to driving down greenhouse gas (GHG) emissions. The California Hydrogen Roadmap and Low Carbon Fuel Standard (LCFS) are key components of California's approach to encouraging renewable hydrogen production and infrastructure [63]. The LCFS offers attractive economics for hydrogen producers and developers and supports the growth of clean hydrogen by providing credits for lowering the carbon intensity of transportation fuels. California. As of 2023, there are 65 hydrogen refuelling stations in California with a goal of 129 by 2029 [64]. Although not without obstacles, such as station reliability, California continues to lead the way on hydrogen infrastructure. California's lawmakers have also made it easier for hydrogen projects to get permits. New laws like SB 1420 have included carbon capture mandates for blue hydrogen projects, continuing to bring hydrogen policies in line with state decarbonisation goals [53]. These initiatives have helped solidify

California as a template for other states hoping to build hydrogen systems. Other states have also outlined unique hydrogen road maps. For instance, New York is prioritising code adoption, safety, and community outreach for developing hydrogen infrastructure and using federal investment to deploy stations. Washington and Colorado are including hydrogen in their larger decarbonisation plans. Colorado's Low-Carbon Hydrogen Roadmap notes hydrogen's potential to help meet Colorado's aggressive greenhouse gas reduction goals by focusing on end-uses where electrification is not feasible. Texas and Louisiana have taken a more industry-centric path, forming hydrogen production task forces and regulatory commissions to evaluate permitting and infrastructure requirements for the hydrogen industry [65]; and these state-level actions mirror the heterogeneous energy economies and priorities among states.

The fragmented system of regulation of hydrogen in the U.S. also gives rise to a number of legal and practical problems. The overlap between federal and state jurisdiction often confounds project development and delays timelines. For instance, hydrogen production plants and pipelines must be approved by state and federal regulatory bodies, each with its own environmental, safety, and land-use standards. State-level attempts to regulate hydrogen infrastructure can also clash with federal regulation, particularly with respect to emissions standards and the siting of energy generation and distribution systems. Section 401 of the Clean Water Act permits states to stop federal projects that could damage water quality, and that can slow the development of hydrogen infrastructure. The Federal Energy Regulatory Commission (FERC) has at times reversed state efforts to advance clean energy, further highlighting the conflict between uniform federal policy and state-led ingenuity [66]. Economic and political hurdles are complicating the task of devising a unified national hydrogen strategy. States with large FF industries might be unwilling to pursue aggressive hydrogen policies, and spatial heterogeneity in renewable resources affects the potential for hydrogen technologies. In addition, uneven regulatory rules for clean hydrogen production and rules governing safe use have led to a patchwork of rules that can discourage investment in and slow progress toward a vibrant clean hydrogen economy.

3.5.3. Japan's Hydrogen Economy Regulations

Japan's hydrogen regulation has been praised for its ambition and systematic arrangement, which is fitting given the country's energy security and climate action imperatives [67],[68]. As a result, the Japanese government has made hydrogen a key element of its decarbonisation strategy, supported by a strong legal and fiscal framework, high public funding, and an original approach to public-private collaboration. Though this regulatory atmosphere has ushered in a great deal of progress, it is accompanied by significant legal, economic, and technological barriers that make the establishment of a competitive and sustainable hydrogen economy challenging. Japan's hydrogen policy is firmly rooted in the adoption of the Basic Hydrogen Strategy in 2017, an unprecedented document that set a worldwide benchmark [69]. This plan charted a three-stage journey: 1) driving the uptake of hydrogen across mobility and stationary fuel cell applications to build a market in the short term; 2) scaling up the supply chain to reduce costs in a maturing market in the mid-term; and 3) a longer-term ambition of a self-sustaining hydrogen market in the UK by 2050. The government set goals for the cost of hydrogen of 30 yen per normal cubic meter by 2030 and also for a hydrogen supply of three million tonnes per year by 2030 and 20 million tonnes in 2050. These goals are supported by interim targets and periodic policy reviews to ensure committed regulatory flexibility. The Hydrogen Society Promotion Act was passed as a regulation in 2024. Two major subsidy forms were formalised by this Act. The contracting side of the rationale: First, the CfD scheme, designed to bridge the price difference between low-carbon hydrogen and traditional hydrocarbon fuels for up to 15 years, enabling long-term price certainty and investment de-risking. Second, the Act provided for regionalisation, which encouraged the co-location of hydrogen production, storage, and end-use infrastructure. These laws are reinforced by tax credits, R&D grants, and capital subsidies. The government has pledged to spend 15 trillion yen ($138 billion) in public and private investment over 15 years toward achieving cost parity between hydrogen and fossil fuels and ensuring the country's technological dominance at home.

A key feature of Japan's hydrogen policy is its emphasis on public-private partnerships. The government has involved key industrial stakeholders, utilities, and research entities in the development of H_2 projects. To this end, some representative examples of the national program are demonstration projects of the MCH (Chiyoda Corporation) supply chain for hydrogen transportation from Brunei to Japan and a demonstration project of Smart City Kobe, where hydrogen is incorporated into the urban energy system. The Woven City initiative, which is spearheaded by Toyota and Eneos, is a model of how green hydrogen can be incorporated to power urban mobility and residential energy. These have been assisted by government funding and enabling legislation, which has included fast-tracking approval processes for demonstration plants and providing access to public land. Thus, the country has built one of the largest hydrogen-refuelling stations in the world, with the number of stations exceeding 130 in operation as of 2024, and the nation has become a world leader for fuel cell vehicle (FCV) deployment. But even with these accomplishments, the rate of infrastructure build-out has, in parts, fallen short of government aims, with operational issues, like station usage and supply chain reliability, presenting challenges. The description in Japanese highlights significant steps forward in Japan's hydrogen regulations, yet its regulatory landscape is not without significant obstacles. First, the issue of cost competitiveness becomes critical. The CfD system does offer a crucial underpinning to prices, but it also contains the potential for long-term subsistence from subsidy and, counterproductively, an impact on stem progression and cost reduction. The stipulation that projects must pay their own way after 15 years could add more uncertainty, not least with hydrogen markets evolving quickly worldwide and potentially disruptive technological leaps happening elsewhere. Second, technical and safety standards pose continuing legal barriers. The modification of conventional laws, including the High-Pressure Gas Safety Act, to apply it to hydrogen is difficult. Certification of new technologies can be expensive and uncertain, delaying commercialisation and increasing compliance costs. In addition, Japan's threshold for "low-carbon hydrogen" ($\leq$3.4 kg CO_2 per kg H_2) is less ambitious than the minimum European benchmarks, which tend to be less than 2.5 kg CO_2 per kg H_2. This inconsistency begs questions about the environmental integrity of subsidised projects and the potential of "greenwashing" as Japan maintains its focus on subsidising fossil-derived hydrogen with carbon capture and storage (CCS). Third, infrastructure and permitting are still in pieces. Although the Hydrogen Society Promotion Act was billed as a means to simplify that, local governments have a high degree of influence over land use and environmental signoffs, making hydrogen inconsistent in deployment. The lack of a national framework for permitting hydrogen pipelines and storage has been identified as a bottleneck to infrastructure expansion, causing delays and increased costs for developers. Fourth, the values of international cooperation and certification; Japan's hydrogen strategy is naturally international, involving imports from Australia, Brunei, and the Middle East [70]. This raises some difficult legal questions on the certification of vehicles crossing borders, on emissions balancing, and on the convergence of safety and environmental norms. The absence of internationally recognised certification systems for “green” or “blue” hydrogen has made it difficult to assure the environmental integrity of import ports and leaves Japan exposed to possible trade and reputational risks. Japan does participate in certain international standard-setting activities, but it has pursued regulatory policies that are less consistent with those of certain of its major trading partners, thus potentially creating market access and supply chain barriers.

3.6. Comparative Analysis of Other Major Jurisdictions

The world's hydrogen transition is a product of an array of legal frameworks and policy regimes, which are proxies for different political economies, stocks of energy, and a philosophy of regulation. This part offers a critical assessment of the hydrogen regulatory landscapes of China, South Korea, and Australia-three jurisdictions that present in stark relief varying legal models that invite further attention as to the promise and peril of hydrogen law and policy. The analysis views best practices, outstanding tensions, and lessons for international harmonisation of hydrogen governance through a comparative, evidence-based lens. China’s posture toward hydrogen is illustrative of the way it handles strategic industries more generally: through top-down planning, heavy investment, and the leveraging of state-owned enterprises (SOEs). The 2022 Plan, a Hydrogen Industry Development Plan (2021–2035) of the central government, was a turning point, as it ultimately incorporates hydrogen into China’s national energy and industrial strategies. The legal regime involves a mix of federal command and provincial innovation. The National Energy Administration and the Ministry of Industry and Information Technology provide broad guidance, but provinces such as Guangdong, Hebei, and Shanghai have unveiled their own roadmaps and pilot regulations that often go beyond national targets. That has led to a fast uptake of infrastructure, with more than 300 hydrogen refuelling stations constructed in China by 2024, the highest in the world. The level of SOE control of hydrogen production and of infrastructure can suppress competition and delay technology innovation, as demonstrated by the slower-than-expected pace of adoption for green hydrogen relative to that of fossil-based production with carbon capture. Also high is the legal uncertainty with hydrogen's classification (as a technical gas or storage) and with safety standards and cross-sectoral integration. In addition, the absence of a single, national low-carbon hydrogen certification system creates the potential for “greenwashing” (the practice of making unfounded or misleading claims about the environmental benefits of products) and complicates trade among countries. Case studies such as Sinopec’s green hydrogen project in the province of Xinjiang and the Zhangjiakou Hydrogen Industrial Park serve as an indication of the sheer magnitude and complexity of China’s strategy. These projects have certainly showcased the ability for rapid state mobilisation, but they also expose regulatory holes in emissions verification and long-term market survival.

South Korea introduced national regulations for hydrogen in 2019 and legislation for the hydrogen economy in 2020 to support the Hydrogen Economy Roadmap (2019), and the hydrogen economy promotion has adopted laws. These laws establish a strong legal foundation for producing, delivering, and using hydrogen and set basic environmental and entry standards. The government’s “Hydrogen Economy Master Plan” has targets of 81,000 fuel cell electric vehicles (FCEVs) and 310 hydrogen refuelling stations by 2025 and 5.26 million tonnes of annual hydrogen production by 2040. South Korea's system has been called a hybrid but is known for its focus on legal certainty and market incentives. The Act also requires hydrogen for public transport fleets and power generation, providing guaranteed demand and de-risking private investment. A key difference is the establishment of a hydrogen certification system that classifies "green," "blue," and "grey" hydrogen according to lifecycle emissions. This brings South Korea in line with international best practice and eases cross-border trade. The law also mandates stringent safety rules led by the Korea Gas Safety Corporation and simplified licensing procedures for hydrogen projects. Notwithstanding these accolades, thornier issues persist. The national hydrogen market is immature, and the high price of green hydrogen production suppresses the competitive power of green hydrogen. Detractors say the government's emphasis on blue hydrogen produced from natural gas with CCS would allow it to further drag its feet on the uptake of genuinely renewable hydrogen. In addition, the speed of change in regulation has, from time to time, been faster than the industry's ability to implement, resulting in implementation clogs. A case study on the introduction of Hyundai's FCV project and the Ulsan Hydrogen City project is also instructive. Both are illustrative of the power of legal clarity and focused incentives in facilitating deployment and of the need for continued adaptation even as underlying technologies and markets change.

Australia's approach to hydrogen is characterised by its market-based process and focus on export. The National Hydrogen Strategy (2019) supplies a malleable framework, with a focus on regulation alignment at federal, state, and territory levels. With its vast renewable resources and proximity to major Asian markets, Australia has set its sights on becoming one of the world's top suppliers of green hydrogen by 2030. The state and federal standards are a patchwork. At the federal level, funding for R&D, demonstration grants, and support for certification and development of standards sits alongside state plans and reforms, as with Western Australia, Queensland, and New South Wales' own hydrogen roadmaps. This fragmented system has allowed innovation to flourish, with more than 90 hydrogen projects announced or underway by 2024, between small pilot plants and large export hubs. Australia's comparative advantages are in regulation and its desire to harmonise with the international community. The government is also working on the creation of hydrogen certification schemes, including the issuance of guarantees of origin that monitor emissions along the hydrogen supply chain, and the certification would be aligned with European and Asian market requirements. That eases cross-border trade and gives credibility to exports of Australian hydrogen. Variations in authorisations, safety regulations, and environmental reviews can create uncertainty and slow the development of new projects from one jurisdiction to another. Industry has complained that there is no national hydrogen act or a single permitting regime to support infrastructure scaling. In addition, the strong export market acceptance in Australia could potentially lead to a failure to develop domestic demand at scale and to lose the chance for hydrogen to integrate into Australian industry and transport. A number of case studies, like the Hydrogen Energy Supply Chain project (HESC) in Victoria and the Asian Renewable Energy Hub in Western Australia, demonstrate the potential of, as well as the challenges associated with, Australia’s approach. These projects illustrate the potential for public-private partnerships and international cooperation, but also underscore the importance of clearer regulatory paths and stronger domestic market signals.

An analysis of China, South Korea, and Australia demonstrates divergence as well as convergence in terms of hydrogen law and policy. China’s top-down model allows for fast deployment but could suffocate competition and innovation; South Korea’s regulatory certainty and national certification help build market confidence but must reconcile the interests of blue and green hydrogen; Australia’s bottom-up approach looks to spark innovation and export readiness but faces regulatory divides and a lack of strong domestic demand. Several policy implications flow from this; legal certainty (from unambiguous and complete regulation to certification schemes) is an investment and an international trade enabler. The second point that needs to be realised is that regulatory agility and harmonisation across government levels are critical to handling technological change and market maturation. Third, adherence to global best practice increases credibility and access to markets, especially those driven by exports. And lastly, a balanced mix of subsidies and market incentives is required to ensure we do not end up with long-term dependence and that we establish a sustainable industry. With the development of the global hydrogen economy, the experiences of these jurisdictions (led by their adaptationism) demonstrate the value of legal frameworks that are flexible and capable of adapting to both domestic needs and international developments. These comparative insights should help inform the next generation of hydrogen regulation so that the law keeps pace with technological and market change.

3.7. Harmonisation of International Hydrogen Legal Frameworks

Challenges to standardising hydrogen regulation worldwide are substantial, including legal, technical, and political issues. One of the first issues is legal fragmentation, the reflection of national interests and energy dependency as a determinate foundation for regulation. For instance, those with large fossil-fuel reserves might prioritise transitional “blue hydrogen”, while others with ample renewables concentrate on “green hydrogen.” This variation makes the search for common definitions, certification schemes, and access to markets difficult, as illustrated by the different strategies taken by the EU, China, and the United States. Advanced economies may have the requirement for highly sustainable hydrogen production criteria, while in the rest of the world, a focus on fast industrialisation and energy access is prevalent. This policy heterogeneity is visible in the patchwork of hydrogen certification: China's hydrogen specifications, the EU's RFNBO specs, California's LCFS, all have various requirements for emissions, verification, reporting, etc [71],[72],[73]. Such inconsistencies hinder international trade, drive up compliance costs, and pose the risk of fragmentation in the market. Another major obstacle is safety and environmental conditions. Inconsistencies in the material of pipelines, the storage procedures, and the accounting of emissions can hamper the inter-regional flow of hydrogen and its derivatives. The launch of ISO/TS 19870 at COP28 in 2023 was one vital step towards the adoption of a commonly agreed-upon methodology for assessing the greenhouse gas (GHG) footprint of hydrogen throughout its life cycle [29],[74]. Lack of anything close to uniform standards also raises the risk of accidents, leakages, damage to the environment, loss of investor confidence, and public trust issues.

Pushing through hydrogen projects in the name of the overriding public interest, as seen in the EU approach in some cases, can lead to the marginalisation of certain groups and to opposition at a local level that can set back, not speed up, project delivery. One-size-fits-all public engagement is inadequate to support all affected communities, making harmonisation commensurately more challenging. Trade law concerns, particularly relating to the World Trade Organisation's (WTO) non-discrimination rules and the TBT Agreement, also make the equation more complicated. Measures incentivising green hydrogen produced domestically relative to imported green hydrogen may contradict WTO obligations, and, given the lack of established practice in this area, a legal foggy cloud remains for both investors and policymakers to navigate. With all these difficulties, much headway is being made through ensuring international and multilateral actions. Leading this trend are the International

Organisation for Standardisation (ISO), International Renewable Energy Agency (IRENA), and International Energy Agency (IEA), which develop common frameworks and modelling. The ISO/TS 19870 standard establishes a universally accepted method for calculating the GHG footprint of hydrogen, enabling transparency and comparison across jurisdictions. Likewise, IRENA's approach to certification governance and cooperative frameworks for certification is seeking to harmonise national schemes and support mutual recognition, a key condition for effective international trade. Bilateral and multilateral pacts have also been important. The EU-China Clean Energy Cooperation Platform and the Clean Energy Ministerial Hydrogen Initiative are good examples of actions to address regulatory barriers and promote technical cooperation. Such agreements typically work towards the harmonisation of definitions, certification criteria, and infrastructure standards, in addition to mechanisms for exchanging best practices in terms of safety and environmental management. The PoS of the EU and the third-party annual certification audits of China, for instance, are oriented to guarantee that hydrogen traded internationally fulfils the agreed environmental and quality standards. At the trade law level, the General Agreement on Tariffs and Trade (GATT)'s TBT Agreement constitutes the core legal infrastructure for non-discrimination under and the use of international standards. But how these principles apply to hydrogen has yet to be tested, and future disputes are sure to centre on the compatibility of national incentives and local content requirements with WTO rules. Not only will the way forward involve technical standardisation, but political consensus is also necessary on fundamentals, including how to define "green hydrogen," the scope of certification, and the trade-off between strictness and flexibility. National regulators are encouraged to harmonise their domestic frameworks with existing international standards, taking into account regional specificities (e.g., regarding resource and socio-economic contexts). The harmonisation of hydrogen law will be indispensable for their development and for the establishment of a transparent, efficient, and durable worldwide hydrogen market.

3.8. Conclusion

This chapter has discussed the developing legal structures related to the global hydrogen economy and identified a great deal of progress as well as ongoing challenges in major jurisdictions. One of the key points revealed is the variety of national approaches to hydrogen: the US, Japan, the EU, China, South Korea, and Australia have each adopted and are pursuing hydrogen regulation set out in separate legal instruments, types of funding, or strategic planning. Those models are represented respectively by the United States, which builds on federal incentives and experimentation at the state level; Japan, characterised by long-term state planning and cooperation between public and private actors; and the European Union, which promotes harmonisation through supranational directives and programmes of certification. China's state-led growth, South Korea's legislative clarity, and Australia's market-led innovation are similarly representative of the range of regulatory approaches. Despite these, some common global legal trends can be identified. Firstly, the momentum for the institutionalisation of hydrogen as a strategic component of national energy and climate policy is palpable, with almost all jurisdictions establishing lofty (if not flyer-friendly) targets for production, infrastructure, and reduction of emissions. Second, governments are also turning to a combination of direct subsidies, tax breaks, and funding for and procurement of R&D to drive both supply and demand. Third, because there is an increasing focus on environmental integrity and on transparency of the marketplace, the number of certification schemes and lifecycle emissions standards has exploded.

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CHAPTER FOUR

REGULATORY ANALYSIS OF ENERGY LAW AND HYDROGEN ECONOMY

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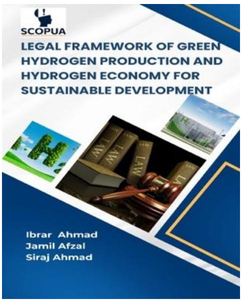

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Abstract

This chapter focuses on the Regulatory Analysis of Energy Law and the Hydrogen Economy. The recent rise of hydrogen as a fundamental component of the world's energy transition has demanded a significant change in energy law. Based on regulating fossil fuels, electricity markets, and grid infrastructure, energy law is in a transitional state as it seeks to accommodate hydrogen. This energy transmitter poses opportunities and challenges for current legal regimes. As countries transition towards decarbonising their energy systems, energy law must facilitate the incorporation of hydrogen into domestic energy systems and the efficient, safe, and sustainable production of hydrogen, its transmission, and distribution. This transition is integral to meeting wider environmental, economic, and geopolitical goals, such as energy security and carbon neutrality, and driving the innovation of clean technology. Energy theory broadly controls the production, transmission, distribution, and use of energy.

Keywords: *Hydrogen Law; Hydrogen Economy; Regulatory Analysis of Hydrogen; Regulatory Analysis of Energy Law*

4.1. Overview of Energy Law in the Context of Hydrogen

Adaptation of the existing regulatory framework to cover the variety of applications of hydrogen is one of the key challenges of energy law [1]. Because hydrogen has a dual function as an energy carrier and storage medium, it has a place in many parts of the energy system, reaching across electricity, gas, and even water management [2]. Regulatory matters, including grid access, priority dispatch for renewable electricity, and grid cost allocation, are essential to facilitate that transition. In addition, legal frameworks will need to contend with regulatory uncertainty in regions where there exists no energy law addressing hydrogen [1]. Unaddressed legal uncertainties hang over the production and transportation of hydrogen, making investment in the industry difficult [3]. Those gaps tend to result in a patchwork of regulations," and that in turn can hamper efforts to get hydrogen technologies to scale. New hydrogen-focused legislation will be central if we are to make a smooth transition to hydrogen in our energy system and create the right investment climate [4]. An important issue for the role of hydrogen in decarbonization is the linkage of its production to renewable energy. Legal frameworks, such as PPAs, are the key to enabling this coupling. PPAs are crucial for the realization of electrolysis projects, as they guarantee a stable supply of renewable electricity, a prerequisite for economical feasibility as well as for guaranteeing that emissions targets are met [5]. The European Union is leading the way in creating the regulatory framework to connect hydrogen production to renewable power [6]. According to the EU's Renewable Energy Directive (RED II) and its proposed revisions, renewable-electrolysis hydrogen does have to fulfil strict criteria regarding additionality, temporal relevance, and geographic proximity [7]. Both of these standards are in place to ensure that renewable energy is not displaced from other applications, such as grid balancing, at the expense of the wider decarbonization effort.

The regulatory framework around green hydrogen certification is also spreading, with the likes of India and Ireland introducing comparable initiatives. Such mechanisms create tighter monitoring of hydrogen's environmental profile, thereby signalling that the hydrogen produced is in line with national and global sustainability goals. But, on the other hand, this is a challenge for legalisation, especially in regions where, so far, no legal framework has been established for hydrogen production [8]. The integration of hydrogen into traditional energy systems is among the most challenging issues in energy law. In many regions, the natural gas distribution network is being considered as a future possible backbone network for hydrogen distribution, through mixtures blending hydrogen and natural gas or by repurposing the infrastructure to operate with pure hydrogen. However, the unique physical characteristics of hydrogen, including differences in energy density and permeability compared to natural gas, require major investments in adjustments to the pipeline network. There must also be legal frameworks to regulate safety standards, material specifications, and operational procedures to ensure that it is safe and feasible to deliver hydrogen within such systems. Within the European Union, measures are taken to modify existing regulations to facilitate hydrogen infrastructure. The Reform of the Gas Directive and Gas Regulation (part of the EU's 'Fit for 55' package) is to establish a specific regulatory framework for hydrogen networks [9]. These measures are intended to secure non-discriminatory access to hydrogen infrastructure, foster competition, and prevent the monopoly of the new fuel. Meanwhile, regulatory sandboxes and pilot projects were being trialled across a number of EU member states that offered key learnings on the on-the-ground hurdles to the integration of hydrogen. The United States, however, is a different regulatory patchwork. Although both the Bipartisan Infrastructure Law and the Inflation Reduction Act included substantial funding for hydrogen hubs, inconsistent regional permitting and safety oversight, and a fragmented approach to infrastructure planning have prevented a coherent national regulatory framework for hydrogen from emerging [10],[11]. To fix the problems, there needs to be better coordination between federal, state, and local government authorities. In addition, a harmonised legal framework for hydrogen infrastructure needs to be established at the national level in order to enable an effective and efficient integration of hydrogen markets [12].

Hydrogen production in particular from electrolysis avails of dominant cross-sectoral impacts: water for utilisation and land for exploitation [13]. Electrolysis involves massive amounts of water and thus legal questions regarding water rights, appropriation, and use. These issues are even more urgent in areas with a shortage

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of water. Energy law will therefore need to be melded with water law under legal regimes so as to avoid hydrogen production becoming another source of water stress or creating new environmental threats [14]. Land use is another important factor to consider. Production and storage of hydrogen facilities and transport and infrastructure can require large areas of land and raise concerns about land availability, zoning, and community issues. At the legal level, laws have to find a compromise between the need to facilitate the fast spread of hydrogen distribution infrastructure and the necessity to ensure public interest and protect environmental values. Open and transparent permitting, stakeholder engagement, and thorough environmental reviews are necessary to address these concerns. Legal instruments, like the EU ETS, provide economic incentives for the hydrogen producers' environmental impact. International cooperation is indispensable, too, for the establishment of a global hydrogen market. The International Energy Agency (IEA), International Renewable Energy Agency (IRENA), and International Organisation for Standardisation (ISO) are already cooperating to standardise technical standards, certification schemes, and definitions of hydrogen [15],[16]. These measures will help to enhance cross-border trade, investment, and innovation and to preserve the environmental performance of hydrogen around the world.

4.2. Energy Transition and Hydrogen: A Legal Perspective

Hydrogen has legal importance in the sense that it helps balance renewable energy systems, offsetting the peaks and troughs, aligning with the solar cycle, for example, helping those sectors we struggle with to electrify (deep sea shipping, say) to decarbonise. For instance, the European Union, in its Hydrogen and Decarbonised Gas Package (2024), mandates multimember cross-border infrastructure planning and implements industrial renewable hydrogen quotas for steel and chemicals, among others. The EU targets a share of 20–50% of fossil-based hydrogen to be replaced by renewable hydrogen by 2030, which reflects the increasing role placed on hydrogen in the journey towards climate neutrality [17]. Similarly, India's National Green Hydrogen Mission (2023) sets a legally binding target for 5 MMT of green hydrogen production per annum by 2030, underpinned by a whopping 125 GW of renewable energy capacity [18]. It is one example of a broader push to place hydrogen into countries' energy transition plans, with country-specific targets and mandates to promote decarbonization. This enables us to highlight key features of these legal frameworks, including the requirement for a strong connection between the production of hydrogen and its application in renewable energies. Under the European Union's Renewable Energy Directive (RED III), hydrogen producers would have to prove "additionality," ensuring that the renewable electricity they used for electrolysis came from new, additional renewable capacity, as opposed to simply replacing clean electricity already in the system.

With hydrogen transitioning from idea to application, energy law is rapidly evolving. Economic stimuli or subsidies are critical to bridging the gap between the costs of green hydrogen (USD 4–6/kg) and fossil-based hydrogen (USD 1–2/kg). For example, the U.S. Inflation Reduction Act provides a $3/kg production tax credit for low-carbon hydrogen if it meets emissions levels and wage standards. They aim to speed up the commercial readiness of green hydrogen, bridge the cost gap and illustrate the legal burden of regulating energy technologies that depend largely on financial support in their early years. Japan's Hydrogen Society Promotion Act (2024) also represents a legal innovation, adding Contracts for Difference (CfD) as measures to bring down the market risks to hydrogen producers [19],[20]. While these factors encourage investment, they bring about medium-term market stability. Are such subsidies and price guarantees a world of international competition? And how much will competition in the marketplace matter in the end? Yet U.S. regulatory issuances also point to the piecemeal regulation that hydrogen continues to face. The U.S. also has a single federal coordination authority, causing delays in hydrogen hub deployment. Meanwhile, state and territory differences in regulations and permit processes are hampering progress, highlighting the urgent need for a joined-up approach to regulation and harmonised permitting at a national level for hydrogen infrastructure.

As hydrogen production increases, the question of energy justice and equity is increasingly salient. Projects that aim to produce hydrogen in places like Sub-Saharan Africa (which could help avert energy poverty by giving clean energy to 600 million people in the world who currently lack access to it) often operate under international acquisition laws (such as India's Land Acquisition Act, 2013) that primarily prioritize corporate interests over the rights of those living on or near the land. This has resulted in the displacement of communities living near the mines; these are marginalised, which is causing concerns about the consequences of the projects. Meanwhile, California's Environmental Justice Equity Principles require local consent for hydrogen projects. We saw it in the rejection of the ARCHES hydrogen hub, which appeared to get public residents onside when their views were poorly managed [21],[22]. The significance of public participation and transparent procedures cannot be overstated, especially when it comes to major infrastructure development projects that have great ramifications for the living conditions of the local population. Second, the Global North-South dynamic on the production of hydrogen adds more equity issues. This initiative encourages revenue-sharing, local resource development, and open governance to help ensure that host countries can benefit from hydrogen production and infrastructure construction. Indigenous rights are also becoming a hot topic on the hydrogen production legal front. One exception is the Hydrogen Valley Initiative in South Africa, which allocates 20% of project revenue to local development [23]. But provisions like these are few and far between, and these should be incorporated into more regulatory frameworks so that hydrogen producers have a type of "equitable" stake.

4.3. Legal Barriers to Hydrogen Integration into Energy Markets

The incorporation of hydrogen into the world's energy markets is subject to intricate, multi-jurisdictional legal challenges preventing its smooth integration into energy systems in many parts of the world. These obstacles are not only technical but also include differences in national regulations, market disintegration, as well as legal uncertainty that challenge the scalability and integration of hydrogen. Related to the above, regulatory fragmentation, a lack of policy coordination, and inconsistent public engagement vehicles create stumbling blocks for the development of a harmonised international hydrogen market. Hydrogen policy and infrastructure development policies of individual countries are considerably based on domestic energy priorities, traditions of regulation on energy, and politics [24]. For example, the French Industrial Emissions Directive requires a high-level environmental impact statement and detailed risk mitigation for hydrogen storage depots of over 1-tonne capacity [25]. Smaller plants are held to less regulatory scrutiny, resulting in inefficiency and uncertainty for developers. In addition, the EU's Hydrogen Backbone project to develop a dedicated hydrogen transport network across Europe has been held back due to incompatible safety standards and national views on how hydrogen can be safely injected into existing pipeline networks. This case study is indicative of the fragmentation of regulation across Europe that prevents a unified and interoperable hydrogen infrastructure.

One of the greatest challenges when it comes to hydrogen deployment is securing the required finance for large-scale projects. The high costs of producing green hydrogen, estimated to be 2-3 times more expensive than hydrogen produced from fossil sources, need large-scale investment. Although there are financial incentives such as subsidies, tax credits, and carbon pricing to help alleviate costs, both policy uncertainty and the absence of long-term regulatory stability are deterrents to investment. In the US, the Inflation Reduction Act (IRA) provides tax benefits for low-carbon hydrogen production; however, changing federal priorities across different administrations results in cyclical policy risk. For instance, tax credits such as 45V are also subject to expiration after 2025, creating uncertainty around longer-term investment returns [26].

The absence of global hydrogen certification standards is harming market consolidation and the creation of a single international hydrogen market. The EU's Renewable Fuels of Non-Biological Origin (RFNBO) standards relating to the certification of renewable hydrogen also have a need for complex details to trace back the renewable electricity source [17]. These regulations put exporters from regions that do not have similar detailed certification systems at a competitive disadvantage. The International Partnership for Hydrogen and Fuel Cells (IPHE) has envisioned the establishment of multilateral arrangements to align carbon footprinting methodology and emissions reporting [27]. As long as these frameworks are not synchronised, we face a risk of market fragmentation and disparate certification standards, which would negate economies of scale and, consequently, would counteract the goal of reducing hydrogen production costs. In Germany, the Hydrogen Acceleration Act (2023) refers to hydrogen projects as 'overriding public interest,' with a fast-tracked approval process, overruling [28],[29]. Although the legislation aims to speed the rollout of hydrogen, it has sparked protests and legal challenges, in particular from communities worried about the environmental and social impact of large schemes. The same problems are occurring in Spain, where shortened environmental approval processes for hydrogen projects in so-called hydrogen valleys are likely to condemn vulnerable communities who rely on the land and water that hydrogen projects consume. The California Hydrogen Highway Initiative provides a good example of broad public participation [30]. It is prescriptive, requiring the consent of a community, and projects incorporate socio-economic factors into the planning process. However, such a model still holds on the margins, and there is a pressing need to encourage the adoption of similarly expansive frameworks that allow for both communities and decarbonization to be pursued. Lack of early and effective stakeholder engagement may result in community alienation and project delays.

4.4. Legal Reforms for Hydrogen Integration

Certain legal reforms are necessary to address the regulatory fragmentation, infrastructure barriers and blocks, and innovation barriers that hamper the role of hydrogen as a key energy vector in the global shift to a low-carbon economy [31]. These reforms, which should fit within an enabling legal framework, need to pave the way for the scaling up and introduction of hydrogen technologies in the market, promote transboundary cooperation, and encourage private investment in green hydrogen production. A harmonised system of certification is necessary to allow cross-border trade to take place and to prevent market fragmentation. Fixing this was a global typology for carbon-intensity thresholds as per the IRENA proposal that might provide a baseline for certifications and limit division of the market [32]. Adopting this global standard would give producers and consumers a legal template, meaning that quality standards could be assured in the same way across the hydrogen trade, lowering the costs of entry for new hydrogen markets. Such multilateral treaties, with the assistance of key global players, would help ensure regulatory convergence across borders. It would take a coordinated effort by both developed and developing nations to reconcile regulatory interests with the imperative to convert economies at scale to hydrogen. A major reform centres around "dynamic" hydrogen project licensing. Models such as the GH_2 Best Practices Legislative Guidance model suggest that hydrogen production licenses should be tied to land use rights and environmental approvals to underpin that production activity will be in line with sustainability targets as well as local regulations [33],[34]. This model that mandates operators to obtain decommissioning financial assurances offers an acceptable trade-off between the scale of operations and safety, a key determinant in the uptake of hydrogen at a large scale. In this respect, the UK's 2023 Energy Act is an innovative piece of legislation. Expanding this license pipeline to hydrogen, the UK sets out a clear regulatory pathway to blending hydrogen into the existing gas system and helping hydrogen producers integrate their product with the key transport networks. Also innovative is the proposed model for financing hydrogen infrastructure projects through the creation of a Hydrogen Levy Administrator in order to lessen the cost burden for developers.

Reclassifying hydrogen infrastructure for what it "is" critical decarbonization assets" and not "hazardous infrastructure" is a critical change that needs to happen to expedite permitting and deployment. This change might contribute to removing the bottlenecks for the deployment of hydrogen infrastructure. California's Hydrogen Highway Initiative provides a useful test case for how reforms to zoning laws can cut through the molasses of permitting and approvals for electrolyser siting and pipeline retrofits, speeding the movement of infrastructure. In addition, the UK's Future System Operator, which will also oversee planning for the hydrogen network from 2026, demonstrates that coordination at the system level is required for hydrogen infrastructure development [35]. A single coordinating body could oversee the development of a technically efficient and regulatorily compliant hydrogen infrastructure and prevent a patchwork of overlapping infrastructure across different regions. Cross-border interoperability is also a major challenge for H_2 integration, especially for Europe [36]. The European Hydrogen Backbone project to set up a continent-wide network of hydrogen pipelines has been hampered by conflicting national rules on compressor design and pipeline pressure, and the project has been delayed. One possible approach is to standardise safety across borders; at the very least, Poland's legal move to put hydrogen into its gas grid with combined transmission tariffs offers just such an example. This pilot could act as a model for further regional cooperation on hydrogen infrastructure roll-out. Internationally, the shipping of hydrogen by sea is also a challenge. Such a lack of clarity could be clarified by adopting IMO-consistent standards for hydrogen tankers [37]. If such regulations could be harmonised, then safety and predictability would be enhanced, with consequent risk reduction associated with hydrogen transport and encouragement of international trade. There is an important role for focused tax measures that drive the production of green hydrogen. The UK's CCL exemption for electrolysis electricity is a £1.2 billion p.a. cost saving illustrates well how fiscal policy can help reduce the economic barriers to the production of green hydrogen [38]. However, these kinds of incentives are only successful if there are serious financing models to remove the risk for new technologies. One promising tool for this could be carbon contracts-for-difference (CCfDs) as a price stabilisation mechanism for investors in green hydrogen projects [39]. Germany's H_2Global, combining CCfDs with import-export auctions, provides security of pricing for the import and export of hydrogen by limiting exposure to changing market prices, which mitigates risk [40]. The Indian Production-Linked Incentive (PLI) program, offering capital grants and transmission waivers, highlights, moreover, the relevance of hybrid financing models when it comes to de-risking investment in hydrogen technologies [41],[42]. They provide producers with an incentive to expand capacity, no longer propped up by the safety net of long-term financial subsidies that help bridge the price gap between green hydrogen and fossil-based counterparts.

4.5. Environmental Law and Hydrogen Production: Sustainability, Compliance, and Standards

4.5.1. Environmental Law and Hydrogen Production: Frameworks and Standards

Embedding hydrogen production within environmental law regimes is complex and involves the consideration of sustainability criteria, mandatory requirements, and evolving standards. Internationally, the Paris Agreement acts as the cornerstone legal document, pushing national and regional hydrogen policies to carbon-neutral energy use. On policy looking toward hydrogen, a leader in hydrogen policy, the EU nests its frameworks in the Paris Agreement's 1.5°C framework through the likes of the Renewable Energy Directive III (RED III) [43],[44]. This target requires us to use renewable feedstocks for 42.5% of hydrogen production by 2030 [45]. The criteria for RFNBO impose even lower lifecycle emissions thresholds, demanding that hydrogen producers reduce their emissions intensity by at least 70% below that of fossil fuels [46]. These are strict measures to prevent greenwashing and guarantee that the hydrogen projects effectively contribute to decarbonization. But there are still barriers in trying to align carbon-intensity scoring for hydrogen production, with cross-border trade a case in point. The International Partnership for Hydrogen and Fuel Cells (IPHE) is working towards setting a global standard for emissions accounting that could be used to harmonise carbon intensity thresholds worldwide [47]. Regulation of hydrogen at the national level is disparate, in line with differing geopolitical and economic conditions in hydrogen-producing states. In the EU, hydrogen production plants making more than 25 tonnes per day are considered "integrated chemical installations" under the Industrial Emissions Directive (IED), which means they must comply with strict emissions limits and apply Best Available Techniques (BAT) [48],[49]. And that not only helps ensure that larger facilities achieve strict environmental standards, but proposed reforms would exempt smaller (less than 60 TPD) electrolysers from some permitting requirements to lower bureaucratic hurdles for the new hydrogen projects on the horizon. In the United States, environmental regulation is fractured, and air emissions and the storage of hazardous material are regulated by the Clean Air Act Title V and the Environmental Protection Agency's (EPA) Risk Management Program (RMP), respectively [50],[51]. OSHA establishes workplace safety regulations, but the absence of a national hydrogen policy means many projects are subject to a patchwork of state-level regulations. Germany's new law for accelerating green hydrogen (Hydrogen Acceleration Act, 2023) has been criticised, and its application was stopped in the courts because of the law waiving community participation [52]. All this suggests a worrisome conjunction between environmental democracy and the requirement for hydrogen infrastructure at the latest notice. The act's emphasis on quick decision-making with little public participation points to the tension between decarbonization ambitions and principled environmental governance. This problem highlights the requirement for more comprehensive rules that allow space for the communities to partake in the decision-making processes while also facilitating the realization of projects promptly.

The production of hydrogen is regulated by a series of pollution control laws that govern emissions, waste, and resource conservation:

- Emissions Monitoring: The Emissions Trading Scheme (ETS) in the European Union mandates that hydrogen plants with production of more than 25 TPD must surrender allowances, encouraging the use of carbon capture technologies. However, the SMR hydrogen production process still has a long way to go to substantially reduce emissions, as it is mainly based on natural gas.
- Waste Management: In the U.S., spent hydrogen production catalysts are also toxic and hazardous and must be disposed of in special facilities at an added cost. This measure relates to the environmental effects of hydrogen production beyond emissions and also includes waste handling.
- Resource Procurement: Governments such as India are tying tax credits on hydrogen production to the purchase of validated renewable power, punishing installations that tap the grid for more than 5% of their power. This policy fosters the development of renewable energy self-sufficiency, but is problematic for fossil-dominant regions. Germany, Community engagement Germany's UVPG mandates a public hearing for projects over 100 MW capacity; this aspect has been criticised, where projects are declared to serve the 'overriding public interest.' Not consulting local communities can result in social unrest, such as the opposition to some hydrogen hubs in Germany. This emphasises the requirement for legal changes to

safeguard representation rights, especially for the communities that might have inherited high risks from the implications of hydrogen production projects.

The GH_2 Standard defines an upper limit for CO_2 of ≤1 kg $CO_2e/kg\ H_2$, mandates 100% renewable power for hydrogen production, and covers human rights due diligence and water stewardship. These criteria are essential to prevent an uncontrolled form of greenwashing by which hydrogen producers give the false impression of being green without being held to rigorous sustainability standards. The EU's RFNBO Delegated Acts implement the temporal relationship for grid-connected electrolysers, stipulating that the renewable electricity used for electrolysis is generated in real-time or near electrolysis. This policy is to tie hydrogen production to actual renewable generation, providing that the hydrogen is green. However, there is much disagreement over the question of temporal correlation, particularly for regions with intermittent renewable resources, like wind and solar. A classification system for hydrogen based on carbon intensity has been suggested by the International Renewable Energy Agency (IRENA). For example, those with a carbon intensity of less than 3 kg $CO_2e/kg\ H_2$ might qualify as "low carbon" hydrogen, replacing the current use of colour definitions. This classification would deliver a more transparent and less subjective understanding of the environmental impact of hydrogen, e.g., in international trade.

4.5.2. Green Hydrogen and Legal Certification Mechanisms

The certification of green hydrogen is essential for its market access in the world's energy markets in order to demonstrate its environmental performance, market transparency and its compliance with legal requirements. The certification of green hydrogen is commonly hampered by varying tracking systems in different regions. Many jurisdictions, particularly in the EU and Japan, employ mass balance systems to account for the movement of renewable energy attributes related to hydrogen production. Although by enabling certification trading, these arrangements also raise the possibility of double-counting renewable energy attributes, resulting in compromised certification quality. In contrast, book-and-claim systems, which are popular in the voluntary market, separate the purchase of renewable energy from its physical delivery to the hydrogen producer. Although it is more flexible, this approach is problematic in that it is hard to confirm that renewable energy has increased generation capacity, so-called additionality. In response to these concerns, emerging blockchain solutions, such as the ones proposed for the EU Guarantees of Origin (GO) system, are being considered to improve traceability and mitigate the risk of fraudulent behaviour. The Zero Carbon Certification in Australia is one such model that leverages blockchain to record and provide authentic proof of hydrogen production and certification, which would help establish market credibility. Yet the intricacies of cross-national certification schemes continue to present a major obstacle to the global hydrogen economy". Differences in emission standards, matching criteria and renewable policy mean that multinational hydrogen projects face a struggle for compliance. Attempts to fill such gaps include the ISO/TS 19870 international standard accounting for GHGs, which has been adopted in 38 countries. Just as this uniform methodology has the advantage of a more consistent GHG accounting approach, it also poses challenges in harmonising standards across regions with different decarbonisation priorities. Multilateral harmonisation has been progressing slowly in diplomatic circles by the IPHE, but is not moving forward as most nations guard their interests and national economic affairs.

The mislabeling of hydrogen as "green" has serious legal implications for producers and the market more broadly. In the EU, non-compliant manufacturers also stand to be excluded from the quotas of the Renewable Energy Directive (RED), prerequisites for being granted subsidies and market drivers. The fines for mislabeling can reach fines worth 200% of the revenue derived from selling mislabeled hydrogen, the EU said, showing it's serious about thwarting greenwashing and will not back down on strict environmental standards for hydrogen. In the U.S., characterising hydrogen as ‘green’ if it isn’t might breach the Federal Trade Commission (FTC) Green Guides, which regulate environmental claims in advertising. Greenwashing hydrogen as a low-carbon product could result in fines under environmental laws, such as the Clean Air Act, and Securities and Exchange Commission (SEC) disclosure rules. The hazards of misbranding do not stop at financial sanctions; additional civil exposures and litigation may stem from consumers or competitors damaged by false representations. It is illustrated by the H2Global v. NRG case in New Zealand, which saw a producer ordered to pay US$2.78m for misleadingly selling hydrogen as green. Instances like this remind us how important certification and market transparency are to avoid legal disputes. Hydrogen certification legal structures will also need strong anti-fraud measures. Authorised audits by accredited organisations such as DNV or Bureau Veritas are essential to enable verification of the sustainability requirements.

4.6. Future of Hydrogen in Environmental and Energy Law

The future of hydrogen energy and environmental law will not simply require incremental regulatory tweaking; it will require a substantive transformation of the law in a coherent and comprehensive fashion. The emergence of hydrogen as a key energy carrier towards climate neutrality and as a central component in the decarbonisation of hard-to-abate sectors, to date resistant to electrification raises complex challenges that cut across traditional legal categories and necessitate original governance models. There is also an issue of balance to contend with, between separating hydrogen infrastructure from traditional fossil gas systems to foster competition while making sure the system remains reliable. And coordinating rules between different levels of national governments, regional entities, and the E.U. can result in confusion and overlap. Global cooperation is essential but fraught because countries have differing priorities and legal traditions. So, we need strong international agreements to align standards, clarify responsibilities, and work through disagreements.

The future of hydrogen law must inspire confidence among investors through clear, stable, and predictable rules. Licensing frameworks, financial protections, and oversight should be consistent from one area to another to prevent companies from exploiting regulatory loopholes. Mechanisms such as Contracts for Difference (CfDs) and carbon contracts-for-difference (CCfDs), as seen in Germany's H2Global program and the EU Hydrogen Bank, illustrate how the law can mitigate risk for investors in nascent hydrogen technologies. Hydrogen production should be thoroughly incorporated into integrated environmental management in future legal structures. This includes applying strict emissions standards, pollution control, and resource conservation laws while incentivising green hydrogen through carbon pricing, subsidies, and certification regimes such as the EU's RFNBO and the GH2 Standard. Further, law should lend to the flexibility and promotion of emerging technologies and circular economy theory, such as waste-to-hydrogen generation and resilient water stewardship systems, in order to increase resource productivity and mitigate environmental degradation. Legal flexibility will be key, having regulatory sandboxes and pilot projects serving as learning laboratories for emerging technologies and new business models.

4.7. Conclusion

This chapter has made clear that energy and environmental law contribute significantly to the advancement of the hydrogen economy. It mapped how changing legal frameworks are dealing with challenging technical, environmental, and market requirements for scaling hydrogen as a sustainable carrier of energy. At the heart of that transition is the need for a common, adaptive policy that takes into consideration the nuanced nature of hydrogen and aligns with worldwide climate ambitions. Energy statutes are adopting more and more hydrogen-specific provisions like customised licensing frameworks, priority grid access rights, or hydrogen infrastructure status as a critical decarbonisation asset, while environmental laws establish stringent emissions measures as well as lifecycle carbon accounting and conservation of resources. Certification standards such as the EU's RFNBO and the GH2 Standard guarantee the environmental robustness of green hydrogen, supported by economic instruments that promote low-carbon production. Going forward, legal regimes should emphasise international harmonisation not only of standards and emissions accounting, support innovation with adaptive permitting, and reconcile the rapid deployment of infrastructure with social equity and environmental justice. New fields, liability regimes and standards, water governance, social and economic impacts, and integration into carbon markets are in need of targeted research and policy shaping.

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CHAPTER FIVE

CRITICAL ANALYSIS OF HYDROGEN ENERGY DEVELOPMENT: GERMANY'S APPROACH TO BALANCING ECONOMIC RIGHTS AND ENVIRONMENTAL SUSTAINABILITY

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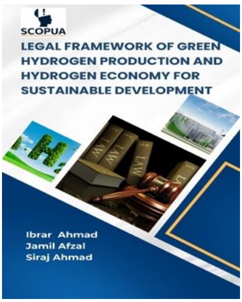

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Abstract

This chapter focuses on Germany’s Approach to Balancing Economic Rights and Environmental Sustainability regarding Hydrogen Energy Development. The German government positions itself as a top global force in clean energy by making hydrogen the fundamental component of its carbon-neutral goals for 2045. The updated National Hydrogen Strategy (Nationale Wasserstoffstrategie) debuted in 2020 and received revisions in 2023 to advance hydrogen production across multiple industrial sectors. The new plan extended Germany's electrolysis target from 5 GW to 10 GW by 2030, alongside 1,800 kilometres of hydrogen pipeline infrastructure development until 2028. Germany plans to become a global leader in the hydrogen economy through its commitment to significant hydrogen initiatives backed by international collaborations.

Keywords: *Balancing Economic Rights; Germany’s Approach to Hydrogen Energy; Germany’s Approach to Hydrogen Energy; Hydrogen Production*

5.1. Introduction

The German government identifies hydrogen as its essential technology to achieve decarbonization in the heavy industry and transport sectors [1]. Storing hydrogen serves as a crucial method to support the operation of renewable energy systems and retain network stability [2]. The economic prospects of hydrogen propel forward significantly as Germany progresses in industrial expansion and job generation through hydrogen development [3]. Germany operates as a hydrogen technology centre to expand its worldwide business competition, together with homegrown innovations [1]. To strengthen its position, Germany collaborates internationally through partnerships that develop supply chains and ensure green hydrogen imports from resource-abundant renewable energy regions [4]. Through these initiatives, Germany reveals its process for hydrogen integration across industrial domains and export platforms.

The German regulatory structure plays a fundamental role in hydrogen development required for energy change, but it still works in a complex environment with many implementation barriers [5]. Germany faces several important obstacles when making their hydrogen infrastructure, which requires the solution of the market's guidance systems for power distribution systems together with safety rules and compatibility of new hydrogen networks [3]. Federal and state regulators maintain separate regulatory frameworks, which create substantial hurdles for hydrogen technology expansion and a stone-blocking national alignment with important European Union standards restricts expansion further. Market cohesion, together with innovation growth, requires the energy industry to maintain policy consistency across multiple levels of governance. Enabling the quick deployment of hydrogen infrastructure throughout the country depends heavily on investment support from both public and private enterprises. The development of security-focused legislative structures represents a critical need since they should give incentives for investments that adhere to environmental and safety regulations. Successful integration of national policies through EU directives by Germany will establish a unified regulatory structure to accelerate the development of its hydrogen economy [6]. Germany's regulatory work toward the hydrogen market will function as a benchmark for other countries working to implement hydrogen technologies [1].

5.2. Germany’s Global Role and Societal Considerations

Germany's role as a leader in global hydrogen transformation depends on its dual commitment to international collaborations and inclusive community participation. Germany builds partnerships with energy-rich nations throughout North Africa and the Middle East to import green hydrogen under its strategic plan [7]. The business partnerships help Germany reach its energy security targets while promoting technology adoption and developing economic growth between Germany with its global partners. Germany's establishment of strategic hydrogen supply networks and trading infrastructure delivers both domestic hydrogen economy leadership and broad decarbonization global progress [3]. Collaborations enable Germany to supply its domestic green hydrogen needs as it develops renewable energy systems across partnering regions.

The adoption of hydrogen technologies in Germany depends on both public acceptance and social involvement at every stage [8]. To gain stakeholder trust regarding hydrogen deployment, it requires clear comments about both its environmental performance and economic merits, as well as definite statements regarding safety standards and sustainability practices. Germany's hydrogen strategy reflects a fundamental goal to provide equitable energy access through efforts that benefit every sector of society. Germany works to develop sustainable and inclusive energy transformation through its hydrogen initiatives, which follow environmental and social priorities [5]. The entire approach aims to address environmental worries together with building stakeholder partnerships, which leads to improved public confidence in hydrogen's role as clean energy.

5.3. Germany's Legal and Regulatory Landscape

The hydrogen energy sector in Germany exists under thorough legal oversight, which runs parallel to EU oversight regulations [9]. The national legislation in Germany focuses its energy system integration around hydrogen through compliance with guideline targets outlined in the National Hydrogen Strategy [1]. The National Hydrogen Strategy aims to solve essential problems from market oversight to safety protocols and infrastructure binding. Safety standards concerning hydrogen technologies throughout their production, stabilisation and transportation chain continue to be central regulatory focus points enabling secure operations. However, Hydrogen's integration into Germany's energy infrastructure faces substantial challenges because the existing power systems need major modifications for hydrogen adoption despite their current focus on fossil fuels.

5.3.1. Alignment with EU and International Agreements

The current hydrogen development frameworks in Germany follow international climate agreements, together with EU directives such as the provisions of the Paris Agreement [10]. Renewable hydrogen serves as an essential component for reaching climate neutrality by 2050, as the EU's Green Deal, along with its hydrogen strategy, recognises its importance for sector decarbonization [11]. Germany actively aligns its national regulatory framework with EU sustainability rules, which define both hydrogen manufacturing methods and end-use standards. However, the EU Delegated Acts on renewable hydrogen specify sustainability standards for green hydrogen that Germany incorporated into its domestic regulatory systems [12]. The established guidelines control the pollution from hydrogen generation processes throughout the manufacturing lifecycle, thus building industry trust in hydrogen as an eco-friendly energy product. The Paris Agreement receives German support through its international collaboration programs and its dedication to climate-driven carbonisation efforts around the world. German efforts to expand hydrogen production with environmental performance goals and stability rules face complex obstacles between economic development requirements.

5.3.2. Balancing Aspects

Complete legal integration ensures that Germany meets its dual goals by protecting the environment while maximising economic capacity from power growth. German policy must reduce market-specific obstacles by solving regulatory ambiguity in order to produce permanent investment structures. Hydrogen projects come from transparent legal models to reduce risk levels before becoming innovative international investments, attracting investors around the world. Additionally, the two countries are facing an important decision to increase their hydrogen production amid the development of economic values and respect the environmental structure established globally. Germany uses legal infrastructure to enable updated electrolysis solutions and the development of carbon capture methods in connection with new technologies. The harmonic hydrogen markets require regulatory frameworks that perform two important functions: First, by uniting the Federal regional EU market rules at all levels of governance and the other, by addressing market fragmentation. The solution to regulatory and financial obstacles depends a lot on cooperation between international institutions. The European Hydrogen Backbone Initiative receives ongoing German participation to develop a pan-European hydrogen transportation system. Through active participation in global decarbonization initiatives, Germany maintains domestic and international alignment of its regulatory framework to deliver hydrogen development solutions [1].

5.4. Challenges in Balancing Economic Growth and Environmental Sustainability

Through hydrogen energy, Germany can generate important economic advantages that establish the country as an influential force in worldwide energy transformation. The H_2 economy development process will create numerous positions across production areas, together with development activities and fundamental study units. The deployment of electrolyzes along with fuel cells and hydrogen pipelines creates industrial development that modernises traditional industries while driving innovation throughout emerging sectors. The combination of Germany's powerful industrial strength with its engineering excellence and clean energy experience positions the country to lead the world in hydrogen technology exports and international expertise. As a result of its hydrogen dedication, Germany has solidified its position among major contributors to global hydrogen economics. Germany's active international partnerships, together with its updated (2023) National Hydrogen Strategy, established country leadership [13]. The emphasis on green hydrogen production from renewable power sources positions Germany to become a global leader in hydrogen markets. The German government creates resilient pathways for sustainable hydrogen import operations by collaborating through trade agreements linking North African and Middle Eastern territories that produce this renewable fuel. German energy security advances through international partnerships to establish leadership within worldwide energy technology innovations [14].

5.4.1. Environmental Challenges

Regardless of their proven market value, modern hydrogen production techniques yield substantial environmental consequences. Manufacturing processes that generate mechanical emissions represent a key environmental challenge in hydrogen production. The rise of green hydrogen as a clean energy solution faces resistance because the renewable energy needs for production require careful assessment of resource availability [15]. Scientists have determined that blue hydrogen production, which includes natural gas processing with carbon capture and storage, cannot be sustained because it maintains dependence on fossil fuels and produces continuous emissions. German authorities require definitive strategies for managing hydrogen manufacturing contaminants to accomplish climate goals. Germany now faces additional obstacles because it needs to fulfil its climate goals by achieving complete carbon neutrality by 2045 [16]. Achieving green hydrogen production objectives requires both raising its production volumes alongside developing market-based hydrogen consumption solutions. Green hydrogen production requires considerable expansion in renewable energy capacity that must proceed without sacrificing renewable-based other industries. We need sustainable management of the environmental aspects of hydrogen infrastructure, from electrolysis water use to renewable energy design and space decisions. Germany needs to solve fundamental difficulties when finding suitable equilibrium points between environmental regulations and economic value considerations in hydrogen infrastructure development [3].

5.4.2. Policy Gaps

The current German hydrogen strategy achieves broad execution but encounters various implementation obstacles that block efficient deployment. Multiple governance regulations present the primary execution challenge because they do not align between central government departments and regional authorities. According to Flath et al., a lack of coordinated decision-making between authorities leads to varying policies that block infrastructure development and restrict investment expansion. Strategy alignment between German federal and local government institutions becomes challenging because of the decentralised system, which delays fundamental technology deployments. Therefore, product distribution applications experience significant implementation challenges because of essential infrastructure restrictions. Because of regulatory uncertainties regarding pipeline development and production plants, together with storage infrastructure development, the planned speed of hydrogen implementation needs to slow down. The delayed investments for 10 GW electrolysis capacity establishment in Germany during 2030 stem from regulatory ambiguities paired with inefficient procedural systems [17],[18]. These regulatory and procedural barriers worsen Germany's current difficulties in transitioning into a hydrogen economy. Thus, environmental priorities battle against economic targets to create new implementation hurdles for policymakers. As industries find new benefits through the hydrogen economic potential, policymakers must address emerging issues of environmental resource management alongside emission reductions affecting policy creation. Germany needs frameworks that support innovative development and funding while constraining activities that deviate from sustainability standards [19]. The development of unified policies that balance economic and environmental aspects stands as critical to resolving these implementation tensions and enabling a sustainable hydrogen transition.

5.5. Recommendations and Policy Proposals

5.5.1. Legal Reforms

Normative legal changes should become the centrepiece of the German strategy to unify rules while enhancing lifecycle emission management in hydrogen development. The major barrier to emission oversight in hydrogen development stems from conflicting regulations between federal-acting authorities and EU directives alignment issues. Putting a government structure in place that coordinates policies, working like Japan's centralised method, will help deliver policies without interruptions across markets. Japan maintains effective hydrogen technology integration through its national target-oriented regulatory system that includes strong federal oversight. The German government should develop standardised life cycle monitoring processes that model South Korea's life cycle assessment protocol. South Korea's carbon accounts do not leave any place for mystery, as each hydrogen production plant should follow a separate protocol with specific environmental criteria that are publicly available. Germany will benefit from installing this feature; the EU standards must match national policy, as it improves regulatory stability, which gives confidence in the market.

5.5.2. Policy Innovations

Germany needs to develop specific signals as well as extended public-private collaboration for private investments to create the hydrogen infrastructure network. Australia reflects success in using public-private partnerships to conduct international trade and technological growth in the hydrogen business through its Hydrogen Energy Supplies Series (HESC) project [20]. Germany should adopt a comparable business model that stimulates private sector participation while maintaining critical international supply channels for green hydrogen. However, Hydrogen infrastructure development needs strategic incentives, including subsidies alongside tax benefits. Through the IRA, the United States gives substantial tax incentives to fuel producers deploying hydrogen technologies and develops infrastructure that utilises hydrogen. By establishing financial rewards for hydrogen pipeline construction alongside storage facility setup and refuelling station deployment, Germany can drive fast market adoption of hydrogen innovations. Additionally, Germany needs to develop stronger international collaborations with hydrogen-abundant regions of North Africa, together with the Middle East [21]. The partnerships must work to obtain hydrogen imports alongside technology and expertise transfer agreements with partner countries. The model used by Australia when partnering with Japan and South Korea presents an opportunity for Germany to develop bilateral agreements that simultaneously support their economy and technology capabilities alongside worldwide hydrogen infrastructure expansion.

5.5.3. Environmental Safeguards

To maintain climate compliance, Germany needs to delegate environmental protections that will guide its hydrogen development initiatives. Lifecycle emissions tracking becomes more efficient through advanced digital technologies when artificial intelligence and blockchain systems perform transparent carbon accounting. Despite the European Union's fundamental lifecycle sustainability criteria, Germany needs to establish more demanding national hydrogen production emission standards. The circular economy deserves attention as a critical arena for German innovation. Germany can build efficiency and reduce resource consumption by reusing waste heat and recycling byproducts, including electrolysis-produced water from its hydrogen production operations. The HyValue initiative in Norway achieves circular economy practice implementation by using industrial symbiosis to optimise resource utility throughout hydrogen production [22],[23].

5.5.4. Supporting Technological Advancements

The sustained leadership position of Germany in the global hydrogen economy depends on the strategic development of supportive legal regulations and policy frameworks. Germany needs to back research and development activities to progress hydrogen technologies, which include both electrolysers and fuel cells and carbon capture systems. The strategic investment of R&D subsidies by South Korea for hydrogen technologies has led to major advancements in affordable hydrogen production approaches [24]. Through targeted funding, Germany should back academic entities alongside startups and industrial leaders conducting hydrogen research projects. Therefore, the strategic development of innovation clusters together with research hubs dedicated to hydrogen technologies would strengthen the relationships between academic institutions, business sectors, and government. The Hydrogen Innovation Centre in Canada serves as an example by linking industry representatives to promote innovation through stakeholder collaboration. Germany should establish identical innovation centres to accelerate hydrogen solution development. However, Germany should join substantive hydrogen research endeavours at an international level. International collaborations with Japan, South Korea and the United States would enable concerted efforts between researchers to gain knowledge which speeds up innovation. Mission Innovation and similar international research programs need Germany's enhanced commitment through elevated hydrogen technology research participation.

5.6. Conclusion and Future Research Directions

5.6.1. Summary of Findings

This chapter demonstrates how hydrogen serves Germany's energy transformation while functioning as a simultaneous economic catalyst and emission reduction instrument. The German National Hydrogen Strategy has made Germany a powerhouse of clean energy by implementing hydrogen solutions throughout transportation and power production sectors and industrial applications. Germany shows its dedication to carbon neutrality by 2045 through comprehensive targets within the strategy, which emphasise expanding electrolysis facilities and developing hydrogen network systems. The study presents several ongoing challenges affecting the balanced transition, such as regulatory complexities, infrastructure limitations and emissions from hydrogen across its lifecycle. However, the critical discovery identifies a fundamental conflict that exists between economy-driven expansion and environmentally sustainable practices. Hydrogen energy delivers substantial economic prospects, including employment generation and industrial expansion; however, governments must execute precise regulation systems to meet strict environmental regulations. To excel in sustainable hydrogen production, Germany must prioritise green hydrogen manufacturing while building consistent policies that integrate domestic aims with European Union requirements for a leadership position in global clean hydrogen manufacturing.

5.6.2. Policy Implications

The study establishes important legal and political changes because Germany goes on to become an international leader in the development of clean energy. The development of hydrogen in Germany depends on the essential elements, including integrated management platforms that should combine the EU and national political adaptation with better emission monitoring for the entire life of the product. German dominance in the hydrogen power market will persist as infrastructure development gains momentum through financial subsidies, coupled with private-public international partnerships and technological progress.[3] German bureaucrats' hydrogen development strategy creates worldwide energy regulatory effects. Options that promote innovation while advancing circular economy principles enable Germany to prove that advanced economic nations can guide global energy transition efforts. The approach, which promotes inclusive renewable energy access and stakeholder partnership, will help Germany become the reference point for countries implementing industrial development frameworks that support environmental sustainability.

5.6.3. Future Research Directions

While this study provides a comprehensive analysis of Germany's legal and policy frameworks for hydrogen energy, several areas warrant further exploration:

- **Stakeholder Perspectives**: The development of future research requires the integration of qualitative evaluation sources from rulemaking bodies and industrial operators as well as environmental advocacy institutions to identify operational challenges and strategic limitations facing the hydrogen sector. Through stakeholder pattern evaluations researchers achieve a deeper comprehension of policy real-world implementation and community reception.

- **Comparative Legal Analysis**: Research into hydrogen strategy execution across Japan South Korea and Australia shows scientists how successful methods and compelling solutions have been implemented in leading economic regions. The hydrogen strategy development for Germany can benefit from analyzing solutions that other leading economies deploy for lifecycle emissions control and infrastructure bottlenecks alongside market regulation barriers.
- **Hydrogen's Socioeconomic Impact**: New studies must explore how hydrogen development will affect employment levels alongside community development needs and social equity measures in environments where resources undergo distributional changes. New research should study the economic and social impacts of hydrogen development so policymakers can develop inclusive strategies that benefit the economy and address societal issues.
- **Technological Advancements**: The advancement of innovative hydrogen technology will need investigation, primarily into future electrolyzes alongside carbon capture systems and digital tracking tools to advance innovation along with reduced operational expenses. Maintaining German leadership in the worldwide hydrogen economy depends on the continued development of these emerging hydrogen technologies.

Lastly, Germany stands at a central moment in its hydrogen transition. Although there has been significant progress in policy formulation, the development of infrastructure and international cooperation, and major regulatory and environmental challenges. The findings from this study have emphasised that Germany should use a strategic, legitimate, and innovative approach to hydrogen development to ensure a permanent and competitive energy future.

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CHAPTER SIX

INTERNATIONAL CONVENTIONS AND REGIONAL TREATIES SHAPING THE HYDROGEN ECONOMY

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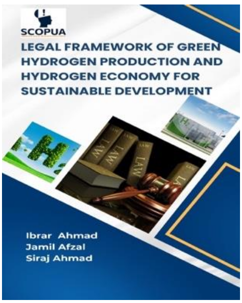

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Abstract

This chapter focused on international conventions for H2 and how regional treaties are shaping the hydrogen economy. This chapter critically examines the role of the United Nations Economic Commission for Europe, the WTO Framework, the International Hydrogen Trade Forum (IHTF), the International Partnership for Hydrogen and Fuel Cells in the Economy, and the Green Hydrogen Legal Capacity Unit (GH2L). To meet their full potential, however, many regulatory, standardisation, and jurisdictional issues will need to be resolved to open up the entire market for hydrogen. Strengthening measures for enforcement, promoting greater international collaboration, and improving legislative frameworks are among the measures needed to overcome these obstacles and to ensure the role of hydrogen as a cornerstone of the worldwide energy transition.

Keywords: *Green Hydrogen; Hydrogen Economy; International Conventions for H2; International Conventions and Hydrogen Production; Regional Treaties and Hydrogen Economy*

6.1. Introduction

International legal regimes, such as treaties, conventions, and agreements, designed to facilitate the production, trade, and investment in hydrogen infrastructure as a clean energy carrier, are essential [1]. Green hydrogen, generated with renewable electricity from wind and solar sources in particular, is emerging as a cornerstone of the global shift towards renewable energy systems [2]. As such, there is a need for coherent international legal frameworks. These frameworks will bring the legal predictability, standardisation, and global cooperation needed to mobilise investment, facilitate cross-border movement of hydrogen, and secure the environmental sustainability of hydrogen production. The international trade law that applies to hydrogen is mainly the United Nations Convention on Contracts for the International Sale of Goods (CISG) [3]. This convention provides a single legal regime for contracts for the sale of goods, including hydrogen, between parties located in different contracting states. By providing uniform rules for the formation of contracts and their interpretation and enforcement, the CISG serves to cut out transaction costs and legal wrangling associated with international trade [3],[4]. However, the CSA does not cover any hydrogen-specific issues like certification or transport standards, which would lead to delays or disputes between the trading partners, while these issues can be negotiated later. The hydrogen trade is also underpinned by the World Trade Organisation (WTO) framework, within the broad principles of trade. WTO pacts GATT and the Agreement on Technical Barriers to Trade (TBT) guarantee non-preferential trade and promote standard harmonisation. Such rules are essential to counteract protectionism that can potentially distort the hydrogen market. Current WTO law, however, does not definitively tackle the comparatively complex legal issues presented by green hydrogen, i.e., how to achieve compliance with environmentally driven standards without generating a discriminatory effect under wealthier challenges (whether relating to subsidies or local content) [5],[6].

International cooperation platforms, such as the Hydrogen Implementing Agreement of the International Energy Agency and the International Hydrogen Trade Forum (IHTF) hosted by UNIDO, also control the governance of the hydrogen economy [7],[8]. These round table discussions promote the exchange between hydrogen buyers and sellers, establish common certification criteria, and align sustainability criteria to form fair and functioning global markets for hydrogen. Especially, the IHTF is preparing to enable nondiscriminatory market access and to develop new hydrogen trade corridors by aligning regulatory approaches and handling socio-economic aspects. On a regional level, the European Union is taking strong measures to create legal instruments that will facilitate the production and trade of green hydrogen. EU legislation RED III and its delegated acts lay down specific criteria for renewable fuels, such as hydrogen, e.g., GHG savings and sustainability [9]. It is these standards that not only apply to domestic production but also to hydrogen imports and that form the basis of shaping global supply chains. Yet the lack of a level playing field in the law, combined with more fragmented rules across the EU and within member states, is holding back the rollout of hydrogen infrastructure at speed. Efforts such as Germany's Hydrogen Acceleration Act are designed to simplify permitting and planning and show how regional approaches can provide examples on the global stage, championing a consistent, hydrogen-supporting legal framework [10],[11]. Environmental law is present in the governance of hydrogen. Certification programs like Green Hydrogen Standard (GH_2) extend well beyond production emissions to encompass social impact, health & safety, governance, and transparency.

However, such efforts have not been enough to knock down real legal barrier walls. The absence of a common framework at the global level is a source of uncertainty for investors and market players. Differences in national regulation, bureaucratic permitting regimes, and varying definitions of green hydrogen are preventing cross-border trade and investment in infrastructure [12]. The fast pace of technological change and the realignment of geopolitical forces only muddle the effort to harmonise law. Closing these legal gaps and aligning legislation is an important task that requires immediate action so that hydrogen can deliver on its full potential to support the global energy transition as well as the climate targets.

6.2. United Nations Economic Commission for Europe: Hydrogen Chapter

The United Nations Economic Commission for Europe (UNECE) is leading the way with hydrogen governance to facilitate the scaling up of hydrogen production, trade, and infrastructure across Europe and potentially other regions [13]. The main objective of UNECE is to promote regional economic integration and sustainable development [14]. As part of its wider work, UNECE is helping to integrate hydrogen into Europe's green transition, which is in line with the efforts of the European Green Deal and global climate goals, contributing to low-carbon hydrogen production and infrastructure. UNECE has a global impact through partnership work with the World Trade Organisation and the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) [15],[16]. In enabling cross-border trade in hydrogen and global cooperation, UNECE has broadened its reach to non-EU members, as well as emerging hydrogen markets in Asia and Africa. One example of such cooperation is in the harmonisation of hydrogen safety standards, where UNECE has assisted countries in Africa to bring their regulatory regimes into line with global best practices. UNECE now joins the likes of the International Renewable Energy Agency (IRENA) and the International Energy Agency (IEA), adding to their focus on technical regulations and infrastructure standards critical to hydrogen's integration in the market [17],[18]. The UNECE Hydrogen Chapter creates ground rules for hydrogen governance. The UNECE Hydrogen Chapter serves as the starting point of hydrogen governance by establishing precise rules for production, trade, infrastructure, and deployment. UN Global Technical Regulation No. 13 (Draft GTR 13) is one of these main provisions: It covers the safety and performance aspects of hydrogen fuel cell vehicles [19],[20]. This legislation is important to advancing cross-border trades because it establishes consistent criteria for certifying hydrogen vehicles.

As for sustainability, UNECE supports hydrogen certification schemes in line with the EU taxonomy for sustainable activities [21]. These systems are intended to demonstrate that hydrogen production is environmentally compliant and meets greenhouse gas emission reduction requirements. At least the certification systems are voluntary in some cases; UNECE will start to promote their implementation through mutual recognition agreements. For instance, UNECE’s hydrogen certification mechanisms have been taken up in Switzerland and Norway, enabling the cross-border trading of clean fuel without compromising the environment [21],[22]. UNECE works with countries in Asia to assist them in integrating such systems into their regulatory regimes, helping to extend the impact of its standards. UNECE has a key role in advancing the cross-border trade of hydrogen, as well as the development of infrastructure, by working to ensure that technical and safety standards are mutually recognised in different regions. Regulatory fragmentation has been a major obstacle to trade; many countries have different safety regulations and certification schemes for hydrogen. UNECE's work to standardise these regulations is contributing to the lowering of these technical barriers and facilitating the transport of hydrogen across borders. For instance, when Germany accepted UN Global Technical Regulation No. 13, over 50 hydrogen vehicles were certified in a two-year period, which then led to increased hydrogen trade with neighbouring markets such as France and the Netherlands [23],[24]. As for infrastructure, UNECE offers technical and legal frameworks for developing places for hydrogen filling stations, pipelines, and reservoir facilities. Safety and interoperability are supported directly from top management downwards, guaranteeing that infrastructure work complies with international standards. Nevertheless, uncertainties remain, notably in Germany, where the federal states are still drawing up their own rules on safety and inspections. These differences impede the rapid deployment of hydrogen infrastructure and thus trade across borders. Looking ahead, in Norway and other regions, the construction of hydrogen refuelling stations has been quickly ramped up, with regional integration of hydrogen markets in which UNECE has been actively involved in streamlining permitting.

The Hydrogen Chapter of UNECE provides a comprehensive regulatory structure, but it encounters several legal and institutional challenges. A key problem is in relation to the market design and aspects such as tariff adjustment and conflict resolution. The lack of an integrated market structure creates opportunities for conflicting tariffs or non-tariff barriers to be applied, which could disturb hydrogen trade. National sovereignty is yet another obstacle. Governments frequently facilitate their national energy policies, which conflict with UNECE's harmonised structure. One example is the Facturation by France's Hydrogen Decree, which creates trade barriers as it diverges from UNECE's common rules [25]. It is difficult to implement UNECE's recommendations, as no enforcement instruments are available. The UNECE framework is based heavily on voluntary adherence to it, and there is no clear way to address the gap between national policies and UNECE standards as a matter of law. In order to overcome these gaps, UNECE may want to consider upgrading the legal instruments by cooperating with international trade institutions such as the WTO and by associating its regulations with global trade agreements that carry clearer enforcement mechanisms. Compared to more comprehensive frameworks, such as WTO agreements or IPHE, the UNECE's Hydrogen Chapter is very technical and region-specific. Although the WTO establishes general ideas and principles applicable to international trade, it does not contain rules tailored to the peculiarities of hydrogen's features, including safety and certification standards. Similarly, IPHE supports research and cooperation but lacks the regulatory depth for trade and infrastructure that UNECE can bring. UNECE's framework has echoes in EU legislation such as RED III, which introduces binding sustainability requirements for hydrogen production and use. Whereas EU RED III addresses sustainability standards, UNECE is committed to harmonising technical regulations and infrastructure. UNECE also works with IRENA and

IEA, integrating its base in the feasibility assumptions to global environmental objectives (like the Paris Agreement). With its support for low-carbon hydrogen production, UNECE is contributing to climate change mitigation and the global energy transition. Real-life cases such as in Germany, France, and Norway illustrate the concrete UNECE-related impact on hydrogen deployment. In Germany, UNECE's incorporation of UN Global Technical Regulation No. 13 has facilitated the certification of more than 50 hydrogen vehicles in 2022, greatly promoting cross-border trade [26]. Also, Norway's infrastructure has already embraced UN Economic Commission for Europe standards, with 20 hydrogen refuelling stations in place to enhance regional connectivity and trade with countries neighbouring the nation [27]. However, there are challenges, especially in non-EU countries and in regions with immature hydrogen markets. Furthermore, a slow rollout in a few EU states makes it more difficult to scale up the hydrogen infrastructure and the market. UNECE's Hydrogen Chapter is critical in the development of the legal and technical environment for the hydrogen economy. Its work facilitating the normalisation of hydrogen regulations, sound environmental practices, and cross-border trade is priceless.

6.3. WTO Framework and Its Influence on Global Green Hydrogen Trade

The World Trade Organisation (WTO) is the main legal framework for regulating international trade, which includes the emergent green hydrogen sector [28],[29]. Two main agreements under the ambit of the WTO are of importance: the General Agreement on Tariffs and Trade (GATT) and the Agreement on Technical Barriers to Trade (TBT). GATT codifies basic trade principles, including non-discrimination, most-favoured-nation (MFN) treatment, and the ban on quantitative restrictions. These same truths can be directly applied to green hydrogen and its derivative products (green ammonia and methanol) and enabling technologies (such as electrolysers and fuel cells). GATT has urged the participants to gradually decrease their tariffs on these products in order to facilitate their free trade across borders and to avoid the implementation of any protectionist policy that might hamper the development of the hydrogen market. However, tariffs on hydrogen-related appliances are quite different between the countries. For instance, even though most developed economies have minimal or no tariffs on electrolysers, emerging markets like India and Brazil still have tariffs upwards of 5% on hydrogen-related technologies. These differences could act as major obstacles to market access, especially in the case of developing countries where tariff protection may restrict the supply of vital technology. In Brazil, high duties for electrolyser imports make it difficult for local hydrogen producers to expand their activities and hamper the rollout of green hydrogen infrastructure and the creation of a competitive hydrogen market. The TBT Agreement is a natural extension of GATT: it addresses technical standards, conformity assessment, and certification. Considering the difficulty of these technologies from a technical perspective, but also from a safety standpoint, the TBT is very important to avoid national regulations turning into hidden barriers to trade. It also calls for WTO members to align their technical standards with widely accepted international standards and use science-based, transparent certification processes. In routine, hydrogen production and transport have been somewhat approached with international standards established by the fighting community of the International Organisation for Standardisation (ISO) and the International Electrotechnical Commission (IEC) [30],[31]. For example, both the ISO 14687, on hydrogen fuel quality, and the IEC 62282, for hydrogen refuelling station safety protocols, create the requisite international technical commonality to support interoperability and cross-border trade [32],[33].

However, the technical barriers of trade are being replaced by concerns over intellectual property (IP) and patent protection.

Subsidies are a particularly thorny aspect of green hydrogen trade within WTO rules [34]. Such subsidies, which could distort trade and trigger disputes, are not allowed under the Agreement on Subsidies and Countervailing Measures (ASCM), which prohibits subsidies contingent upon export performance and local content requirements. However, the WTO has acknowledged that "green" subsidies that promote clean energy, such as green hydrogen, are necessary for meeting climate objectives and could be allowed if designed in a non-discriminatory way [35],[36]. Multiple nations, from Germany and Japan to the United States, have begun offering large subsidies to jump-start green hydrogen production and infrastructure. For its part, Germany has set aside billions of euros for green hydrogen infrastructure, with subsidies for electrolyser manufacturing and refuelling stations. However, there have been concerns about these subsidies being biased in favour of the produce in the domestic market. For example, subsidies that stimulate local content could potentially breach WTO rules of non-discrimination if, at the expense of foreign suppliers, the subsidies go in favor of the country where they have been implemented. Real-world cases, such as the EU–US trade row on renewable energy subsidies or China's electric vehicle subsidies, demonstrate the precedence of scrutiny of subsidy structures under WTO rules, and the same could happen with green hydrogen subsidies. Local content requirements could pose a major challenge in some developing countries as they try to spur local industry. Countries such as India, China, and South Africa have introduced local content requirements in their renewable energy and green hydrogen industries, but these can be inconsistent with the WTO's non-discrimination regulations. The WTO's system for resolving disputes is a linchpin for enforcing trade rules and settling conflicts. No disputes have so far arisen with regard to green hydrogen, but lessons can be drawn from other clean energy industries. In DS456, United States–Solar Panels, the WTO found against specific U.S. subsidies that discriminated against foreign producers by giving preference to domestically produced goods and called for policy reform [37]. So too did Canada–Renewable Energy (DS412), centred upon Ontario's local content requirements, which were deemed to be discriminatory [38]. These cases serve as examples of how the WTO examines subsidies and trade limitations that distort markets and will set a blueprint for future disputes over the trade in green hydrogen. If countries like the U.S. or China give subsidies to their national green hydrogen producers, such WTO challenges may come about, underscoring the importance of respecting international trade obligations.

6.4. United Nations Industrial Development Organisation (UNIDO): International Hydrogen Trade Forum (IHTF)

Various key international entities, including the United Nations Industrial Development Organisation (UNIDO) and the International Hydrogen Trade Forum, are actively facilitating the acceleration of the global hydrogen economy [39],[40]. UNIDO is contributing significantly to supporting the use of hydrogen technologies in developing countries [41],[42]. Mainly via capacity development, policy advisory, and technical support, it supports countries in the integration of hydrogen technologies into the energy system. This involved, for instance, initiatives in Morocco and South Africa, where UNIDO supported the creation of the hydrogen infrastructure through the generation of power from locally available renewable sources [43],[44]. But there are also a number of obstacles that the organisation faces. The explanation is financial, a lack of technical expertise in most developing countries and a lack of existing infrastructure. While the levels of UNIDO's contributions were current, the majority of programs were driven to deliver quick wins. Nor do they provide the level of sufficiency necessary to enable locally driven hydrogen industries to stand on their right. In order to enforce such a mechanism, there is a requirement for financial restructuring that could be accomplished by new financial programs. Potential sources of finance are multilateral development banks and private sector investment. Besides the market, IHTF is crucially engaged in regulating the international hydrogen market development by standardisation of regulation and implementation of certification and certification processes, as well as in governance of environmental issues throughout the hydrogen value chain. The measures have also been introduced in order to prevent market fragmentation and to support the trade in hydrogen among producers, consumers, and traders. But, as of now, the biggest impediment to trade in hydrogen across borders is the fragmentation of regulatory regimes. There are different national regulations on the safety, transport, and environmental effects of hydrogen. For example, the legal system of Europe is distinct from that of Asia or Africa.

Regional hydrogen hubs are essential to maximising the use of local, renewable resources to produce hydrogen for domestic and overseas markets [45]. In areas such as Southern Africa and Latin America, with vast renewable energy potential, hydrogen production could have a central role in delivering on both energy and economic objectives [46],[47]. The promotion of these regional hydrogen hubs by IHTF, by standardising technical standards and reducing regional agreements, is very important. Fleshing out specific cases, specifically in resource-abundant regions, will enable us to comprehend the factors involved in regional hydrogen development and the policy measures needed to address local impediments to market integration. MDBs like the World Bank and the Asian Infrastructure Investment Bank (AIIB) play a crucial role in funding H_2 projects in emerging economies [48],[49]. These banks offer loans at attractive terms, grants, and risk-sharing facilities that reduce financial uncertainties and support hydrogen infrastructure investments. While the section on MDBs briefly describes MDBs' roles, an analysis of how MDBs de-risk projects in capital-scarce areas would add value to the discussion. Concrete examples of MDB-financed hydrogen infrastructure projects, such as AIIB's assistance in Asia or the World Bank's blended finance efforts in Africa, will illustrate the real added value of MDBs in promoting green hydrogen projects in developing countries.

UNIDO and IHTF are essential parts of the emerging hydrogen economy in the world. UNIDO's capacity-building activities and those of the IHTF have built momentum for a more connected and sustainable hydrogen market. Yet, major challenges persist chiefly in financial viability, regulatory fragmentation, and market power. To overcome these challenges, UNIDO needs to prioritise the establishment of sustainable funding mechanisms that lessen dependence on external assistance. Moreover, more needs to be done to converge regulatory frameworks across geographies and to mobilise H_2 activities in the private sector. Leveraging MDBs as sources of finance for hydrogen infrastructure and developing regional hydrogen hubs will also be key to realising the full potential of the global hydrogen economy.

6.5. International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE)

The International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) was launched in 2003 and is a significant global collaboration to accelerate progress in the development and deployment of hydrogen and fuel cell technologies [50]. The IPHE works to foster the transition to clean energy systems and the use of hydrogen as a sustainable, clean energy solution for a variety of sectors, including those such as transportation, energy storage, and heavy industry [51]. IPHE facilitates worldwide collaboration and information sharing for the purpose of promoting the transition to clean and efficient hydrogen systems within the framework of sustainable development. IPHE coordinates and promotes research and development in hydrogen technologies. IPHE has been a leading force in developing the international hydrogen community by promoting RD&D, international collaboration, and the commercialisation of hydrogen technologies. One of the greatest advantages of IPHE is its addressing the standardisation of hydrogen technologies. By collaborating with global entities, including ISO and IEC, the IPHE has promoted the creation and implementation of worldwide standards for hydrogen production, storage, delivery, and safety. Such standards are important in lowering technical trade barriers and promoting cross-border interoperability, key to the creation of a global hydrogen economy.

IPHE is also promoting the use of renewable (green) hydrogen, including via collaboration with partners like the International Renewable Energy Agency (IRENA) [18]. The work of IPHE to align hydrogen efforts with the objectives of the Paris Agreement and other global sustainability regimes advances the deployment of low-emission alternatives. Specifically, IPHE contributes to a sustainable energy transition because of its commitment to the promotion of green hydrogen production and to the decarbonization targets of a wide variety of industry sectors. Legal and regulatory harmonisation is central to IPHE's efforts to enable international hydrogen trade [28],[52]. The association aggressively seeks to align legislation, making sure that member countries' national laws are consistent with those of the international community. Taking action to help unify such policy activities, IPHE aims to develop and harmonise safety codes, certification procedures, and environmental standards, one of the key obstacles on the road to hydrogen trade. IMTA is in favor of the development of international standards that become accepted worldwide, aligning regulatory governments and adding an element of predictability for market participants. For instance, by also working together with ISO and IEC, the IPHE ensures that technologies for producing hydrogen, storing it, and transporting it are covered by similar safety and performance standards, which helps to increase the proliferation of hydrogen infrastructure across borders. This alignment creates confidence for investors and market participants, supporting the development and expansion of hydrogen markets globally.

IPHE has played a key role in promoting hydrogen development in different parts of the world by supporting strategic partnerships. In particular, IPHE's partnership with the United Nations Industrial Development Organisation (UNIDO) is designed to support hydrogen implementation in regions with developing economies. The IPHE has had a visible effect on the worldwide hydrogen market by stimulating international cooperation and market visibility. Through converging regulation and encouraging standardisation, IPHE has stimulated investor confidence in hydrogen. The partnership's work to develop global safety standards and promote interoperability has lowered risk and uncertainty, making the market more likely to attract private-sector capital investments. IPHE plays a key role in the transition to a global hydrogen economy as a forum for the coordination of international policies, sharing of best practices, and promotion of the internationalisation of new hydrogen codes, standards, and safety practices. Through its activities promoting green hydrogen infrastructure and regulatory alignment, IPHE supports the development of a sustainable and connected global hydrogen economy.

6.6. The Green Hydrogen Legal Capacity Unit (GH2L): Advancing Legal Frameworks and Market Integration for Green Hydrogen

The Green Hydrogen Legal Capacity Unit (GH2L) has been created to fill the crucial lacuna in legal and regulatory expertise and framework that is vital to expedite and support large-scale renewable energy and green hydrogen projects, especially in the developing world. GH2L forms part of the wider GH2 project and aims to deliver high-quality, affordable legal advice and support to governments and stakeholders, supporting them to create strong and transparent legal and regulatory structures, which can help unlock the potential for development set out in the green hydrogen scenario. GH2L's main aim is to support sustainable energy transitions in line with global climate conventions, including the Paris Agreement and SDG 7, to ensure access to affordable, reliable, sustainable, and modern energy for all. This strategic focus ensures that GH2L initiatives will advance global decarbonization through the adoption of green hydrogen in national energy systems around the world. GH2L has a key role in addressing legal and regulatory barriers that hinder investment in green hydrogen infrastructure or delay it. By helping governments develop clear regulations, policies, licensing, and regulatory oversight approaches for hydrogen use in their national and international energy systems, GH2L works to ensure that the integration of hydrogen as an energy carrier is legally robust and supports sustainable development. This is especially important for LDCs and EMDEs, which often do not have the institutional capacity to quickly develop the complex legal framework that is essential for hosting large-scale green hydrogen projects. In their work, GH2L is legislating and implementing laws that support and meet the specific needs of green hydrogen technologies and markets. This could include advice to governments on creating regulatory regimes for hydrogen production, distribution, and storage, for example, by introducing licensing regimes to achieve a balance between state control and market flexibility. This will require, among others, independent regulators with specific mandates to oversee market activity, enforce compliance, and verify “green” hydrogen claims via guarantee of origin (GO) systems, which are critical for ensuring market transparency and boosting investor confidence.

Even though these frameworks have worked reasonably well, there are considerable challenges to harmonising them across such diverse jurisdictions with differently developed legal systems. GH2L, therefore, provides the needed navigational power in these disparities by providing tailor-made advice such that the frameworks are practical and implementable. Moreover, GH2L has been instrumental in the creation of legal frameworks that support project development and financing, a vital aspect that goes beyond legislation. Please contact us to help with managing and negotiating offtake agreements, PPAs, equipment supply, and financing that are based on best practices and risk allocation. GH2L, for instance, has counselled on offtake agreements for Morocco projects, as well as “take-or-pay” agreements to protect the interests of investors while closely attuned to state-sponsored incentives that would jive with national energy policies. Capacity-building activities involve legal training, model clauses for contracts, and policy development tools for the public and private sectors to structure complex green hydrogen project agreements. GH2L engages as an active partner with a variety of international organisations, governments, and private industries to clarify global legal standards and market environments. It also collaborates with the European Union, the International Renewable Energy Agency (IRENA), and the International Organisation for Standardisation (ISO) to spread and adopt the development of harmonised legal protocol and certification systems. They do so by helping interconnect green hydrogen markets through regulatory cooperation and achieving mutual recognition of sustainability certificates. For instance, the work GH2L has performed with IRENA has resulted in the development of a scalable regulatory regime for hydrogen production, which has been instituted in a number of African nations. These partnerships are actively assisting in the build-up of hydrogen infrastructure, cross-border trade, and efforts to enhance foreign investment inflows.

6.7. Regional Treaties Supporting Green Hydrogen Production and Market Integration

6.7.1. Regional Treaties Promoting Green Hydrogen Production

Regional treaties and strategic alliances are emerging as key factors for advancing green hydrogen production by setting clear objectives, establishing cooperative frameworks, and mobilising required financial and political resources. Within Europe, the EU Hydrogen Strategy, which was unveiled as part of the European Green Deal last year, has developed into a solid regional framework [53]. It is hoping to deliver 10 million tonnes of renewable hydrogen per year by 2030 and to deploy 40 gigawatts (GW) of electrolyser capacity in the EU countries [54]. The EU Hydrogen Backbone initiative has so far identified more than 3,000 km of hydrogen pipelines and is expanding up to 6,800 km by 2030, to enable the transport of hydrogen across borders at a large scale [55]. A cornerstone of this is the European Clean Hydrogen Alliance, which has brought together more than 750 hydrogen projects across the EU to develop a cross-border value chain and ensure that investment is channelled towards the EU's renewable hydrogen objectives [56]. These initiatives receive EU financing through the European Structural and Investment Funds, the Connecting Europe Facility, and the Innovation Fund. The commitment to green hydrogen of the EU has not only further galvanised the internal market, but has also carved out an increased demonstration space for the EU gas industry as a global model and a place to develop and innovate hydrogen technologies. In the Asia-Pacific (APAC) region, the APAC Green Hydrogen Alliance, which was established by the Green Hydrogen Organisation (GH2) in collaboration with Breakthrough Energy, comprises countries such as Australia, Japan, South Korea, Indonesia, and Singapore [57],[58]. The alliance is committed to promoting facilitative policies, harmonising regulatory standards, and enabling financing measures that should help ensure the scalability of hydrogen production at industrial clusters. It further seeks to establish APAC as a hydrogen export corridor within the region and to global markets so that APAC can not only become the foremost hydrogen producer but also a major player in the global hydrogen marketplace. The Middle East and North Africa (MENA) region is no less ambitious, as Saudi Arabia, Egypt, and Morocco have all targeted 10 million tonnes per year of green hydrogen output by 2030 [59]. Saudi Arabia has its own NEOM project, funded by the Public Investment Fund, which perfectly illustrates a move in this direction, leveraging the region's plentiful renewable resources, particularly the abundant solar and wind available [60]. Moreover, the Africa Green Hydrogen Alliance (AGHA), including Egypt, Kenya, Morocco, Namibia, and South Africa, aims to position Africa as a major global player in green hydrogen by aligning policy, certification systems, and regional cooperation, making it easier to export hydrogen to Europe and Asia.

6.7.2. Legal and Regulatory Frameworks under Regional Treaties

It is important to develop legal and regulatory regimes based on such regional treaties to foster green hydrogen production and guarantee the stability of the emerging market. The Renewable

Energy Directive II (RED II) of the EU specifies specific sustainability requirements as well as the requirement to use Guarantees of Origin (GO) for renewable hydrogen [30],[61]. This method of certification ensures transparent accounting and eliminates double-counting, instilling confidence in both investors and consumers. Meanwhile, the Alternative Fuels Infrastructure Regulation (AFIR) requires the rollout of refuelling stations with hydrogen every 200 km on the continent's core network for road transport by the decade's end, integrating hydrogen into the European transport landscape [62],[63]. The APAC Green Hydrogen Alliance supports the convergence of regulations, the development of consistent licensing regimes, and environmental protocols in hydrogen production across Asia-Pacific. Such a harmonised regulation method enables member states not only to achieve the highest hydrogen production and trade but also to counteract the legal (uncertain regulatory environment) and market (distorted competitive environment) challenges that different regulatory structures create. Cross-border Hydrogen Trade: APAC's alignment of national policies paves the way for the establishment of robust legal frameworks to support the trade of hydrogen between countries and further investment. Also in Africa, AGHA has played a leading role in stimulating regulatory harmonization within member states. The harmonization of policies and regulatory frameworks helps to lower investment hurdles and allows African countries to ramp up their hydrogen production. In addition, adhering to global sustainability metrics allows Africa's hydrogen to satisfy worldwide certification, thereby allowing the region to export to global markets.

6.7.3. Infrastructure Development Supported by Regional Treaties

Creating hydrogen infrastructure is key for the expansion of green hydrogen, and regional agreements are important drivers.

Among the most ambitious is the vision of the EU Hydrogen Backbone project, which aims to establish a continent-wide network of hydrogen pipelines. In 2030, more than 6,800 km of hydrogen pipeline will be in operation, connecting hydrogen production and consumption sites and enabling the cost-effectiveness of transport between countries [64],[65]. With distances exceeding 3,300 km, the South Corridor (a cross-border project connecting North African renewable hydrogen to Europe) from Africa to Europe will supply 5 GW of renewable hydrogen to Europe securely in 2030 [66],[67]. These facilities are examples of how regional agreements are critical for the large-scale production and transport of hydrogen. For Africa, AGHA is working on the creation of hydrogen production units together with the transportation system needed to allow the export of massive quantities of hydrogen. AGHA is involved in obtaining regulatory approval, financing, and exploiting the continent's considerable renewable energy resources for use in the projects.

6.7.4. Regional Collaboration and Knowledge Sharing

Regional pacts foster cooperation and sharing of knowledge, essential to expedite the growth of hydrogen technology. In the EU, there is Horizon Europe, which supports research and innovation in projects devoted to improving the efficiency of the electrolyser and technologies for hydrogen storage and fuel cells [68],[69]. These projects frequently include international consortia, resulting in the transnational sharing of knowledge and the development of technology. The APAC Green Hydrogen Alliance supports governments, academia, and industry working together towards the establishment of best practice legislation, contracting, and sustainability standards. These projects help make sure that hydrogen projects are developed efficiently and in compliance with environmental requirements. It also enables new markets to apply the best practices implemented in proven markets.

In Africa, AGHA's capacity-building initiatives offer technical support and knowledge-sharing to support local governments, states, and non-state actors in the challenges of producing hydrogen and coupling to the markets and regulatory systems.

6.7.5. Financing Mechanisms and Investment

Financing is a critical enabler for green hydrogen projects, and regional accords serve as a major catalyst for capital provision. The EU also has financial instruments such as the Innovation Fund, InvestEU, and Next Generation EU to back hydrogen projects. These financial resources offer grants, loans, and guarantees to backstop hydrogen projects as they secure the needed capital. For example, the Innovation Fund has set aside more than €2.8 billion for hydrogen across its projects, enough to help create a new industry and infrastructure [70],[71]. In APAC, the APAC Green Hydrogen Alliance targets both public and private sector actors to activate capital. The coalition encourages enabling policies required for the large-scale investments necessary to scale hydrogen production. Private investors, including big energy companies, have also been key to funding hydrogen in the region. The partnership collaborates closely with multilateral development banks and donor collaboration to deliver concessional finance and risk mitigation tools. These actions contribute to unlocking investments in hydrogen infrastructure projects, in particular in areas with reduced access to traditional forms of investment.

6.8. Conclusion

To conclude, we can say that International Conventions and Regional Treaties are playing a positive role in shaping the dynamic of the hydrogen economy. Regional agreements have helped to scale green hydrogen production, though these come with their challenges. In Europe, the EU Hydrogen Strategy has initiated more than 750 investment projects and is fuelling the rapid expansion of hydrogen infrastructure through projects such as the hydrogen backbone. The South2 Corridor will be operational by 2030, with which the large-scale export of renewable hydrogen from Africa to Europe will become a fact. Africa (via AGHA) has made strides towards policy alignment and pilot establishment. However, problems such as financing shortfalls, fragmented regulations, and infrastructure constraints remain. They can be tackled to an extent using regional agreements, which feature harmonised policy frameworks and stimulate investment in hydrogen infrastructure, but implementation schedules can be pushed back by geopolitics and economics. Regional agreements in Europe, Asia-Pacific, MENA, and Africa have helped to catalyse green hydrogen production through the creation of a legal framework and related infrastructure build-out and financing. Although these efforts are propelling the global green hydrogen economy, challenges, including the high level of regulatory fragmentation, funding shortfalls, and geopolitical tensions, persist. Engagement of the private sector is necessary to address these barriers and to scale hydrogen production. The further fortification of these regional agreements is going to be crucial if we are to scale green hydrogen production to meet global decarbonization ambitions.

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CHAPTER SEVEN

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

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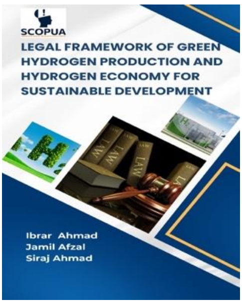

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Abstract

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 electrolysers 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 electrolysers 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 electrolysers, 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 H_2 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 crossboundary 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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