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Novel Maturity Scoring for Hydrogen Standards and Economy in G20

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Abstract

The absence of a universally accepted hydrogen standard and policy inconsistency hinders the development of a hydrogen economy, trade, and the achievement of net-zero targets across G20 nations. Such regulatory inconsistencies create challenges in policy alignment for investment, infrastructure compatibility, and market forecasting. This study addresses key gaps by performing a comprehensive assessment of hydrogen standards - both local and international - financial allocations, national hydrogen strategies, and future plans for fostering sustainable hydrogen economies within the G20. A maturity scoring approach, employing the Weighted Scoring Model (WSM), is utilized to rank each country from 1 (indicating lowest maturity) to 10 (indicating highest maturity) based on performance across these criteria. Results show that the United States and China, each scoring 10, are the most mature G20 nations in hydrogen economy development, while Mexico scored 1 across all criteria. While only the United States, China, and the United Kingdom have formally released hydrogen standards, countries such as Australia, France, Germany, and Italy demonstrate significant advancements. The review shows that some nations, like Japan (strategy and plan 8, investment 1), have uneven maturity across criteria, with similar patterns in Brazil, South Africa, Russia, Argentina and India. This analysis offers vital guidance for governments and policymakers to advance hydrogen economy policies aligned with global net-zero and sustainability goals. It supports Sustainable Development Goals like Affordable and Clean Energy, Climate Action, and Sustainable Cities and Communities, emphasizing the need for a unified hydrogen standard to drive progress in G20 nations.

Highlights:

- Hydrogen standards and economy in G20 are assessed via novel maturity scoring
- Hydrogen legislation, investment, strategy and plan are the main criteria assessed
- Heterogeneity of hydrogen standards and legislation across G20 is found

- United States and China are most mature in hydrogen economy development amongst G20
- Critical insights for governments and policymakers to enhance hydrogen economy

Keywords: Hydrogen standard; Hydrogen economy; Investment; Hydrogen strategy; Maturity scoring; G20

Word Count: 24267

Abbreviations

Austrade	Australian Trade and Investment Commission
CCUS	Carbon capture, utilization, and sequestration
CISRO	Commonwealth Scientific and Industrial Research Organisation
CSWG	Hydrogen Codes and Standards Working Group
DEA	The Department of Environmental Affairs of South Africa
DOE	Department of Energy
EMRA	Energy Market Regulatory Authority of Turkey
EU	European Union
GH2	Green hydrogen
GHG	Greenhouse gases
GVA	Gross Value Added
HBD	Hydrogen Business Desk
HFTO	Hydrogen and Fuel Cell Technologies Office
HyNet	Hydrogen Energy Network
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IESA	Indian Energy Storage Alliance
IRENA	The International Renewable Energy Agency
ISA	International Solar Alliance
ISO	International Organization for Standardization
LCHS	The UK Low Carbon Hydrogen Standard
MCTI	Ministry of Science, Technology, and Innovation of Brazil
MENR	the Ministry of Energy and Natural Resources of Turkey
METI	The Ministry of Economy, Trade and Industry of Japan

MME	Ministry of Mines and Energy
NRRP	National Recovery and Resilience Plan
NZHF	The UK Net Zero Hydrogen Fund
R&D	Research and development

1. Introduction

The realization of the United Nations' sustainable improvement goals heavily relies on the crucial advancement of more sustainable renewable-based energy applications [1]. The challenges associated with reducing emissions in energy-related sectors stem substantially from the high universal dependency on fossil fuels. This reliance has led to substantial CO_2 emissions in different sectors [2]. Rapid population growth and economic expansion are driving higher energy demands, intensifying resource scarcity, environmental degradation, and global economic risks [3, 4]. Utilizing renewable energy resources is crucial due to the limited availability of fossil fuels and the environmental harm caused by their use [5, 6]. An essential approach to addressing climate change involves creating a low-carbon economy, aiming to decrease energy usage, minimize pollution, and reduce the release of greenhouse gases (GHGs) into the atmosphere [7]. Transitioning to technologies that possess greater environmentally favourable attributes is preferable [8]. The utilization of renewable energies is gaining widespread acceptance and adoption as a significant energy source [9-11]. In practice, a disparity exists between the current proportion and the ideal amount of global renewable energy utilization [12]. Renewable-based energy resources have been considered as an alternative option for fossil and pollutant fuels to meet continuing rising energy demand. To supply needed energy for different systems and applications, hydrogen stands out as one of the most promising choices for fulfilling the role of an energy carrier [13, 14]. Hydrogen is one of the most promising technologies that has attracted industries, government, stockholders, and academic sectors' attention to be considered as a low-carbon energy source to supply needed energy for industries, buildings, and transportation. Hydrogen could become a main energy carrier in the future because of its capability and flexibility to be linked with natural gas-based systems, as well as supplying carbon-free for vehicles on long-distance journeys [15-17]. Unlike renewable electricity, green hydrogen (GH2) does not have an established market at present [18]. One of the main barriers to this challenge is the lack of a unified international standard for GH2. Then creating a globally accepted legislation and standard for hydrogen trade is essential. According to the International Renewable Energy Agency (IRENA) report, no hydrogen certificate is applicable for international trade [19]. Another main issue is the lack of sufficient information and details in standards for a proper comparison of cross-border standards due to gaps in standard design, and ecolabelling [19]. The most significant gaps are [19]:

- A unique ecolabelling approach
- Exact and explicit information related to GHG emissions of hydrogen production and transportation
- Compatibility of a unique standard with social, governance, and environmental benchmark
- Implementing a unique certification

It is expected that hydrogen will play an influential role in the future of energy sectors [20]. It is necessary to establish proper legislation, regulations, and standards to effectively apply fuel cell and hydrogen generator technologies in transportation and energy systems in an effective and affordable way [21].

Standards are designed to provide clear definitions that guarantee the compatibility of related components. These standards are established through a formal agreement on their scope and content by the entities responsible for their creation, commonly called standards-developing organizations [21]. Standards are essential for establishing a secure, market-ready environment to deploy commercial hydrogen technologies [22]. Standards have the potential to enable a unified approach to market access, manufacturing, and widespread application. Typically, standards should focus on performance rather than specific design requirements [21]. Based on the International Energy Agency (IEA) report, five principal policy categories have been defined to scale up the hydrogen economy as follows [23]:

- Setting targets and providing long-term policy signals
- Creating demand for hydrogen
- Mitigating investment risks
- Supporting research and development (R&D), strategic demonstration projects, and knowledge sharing
- Promoting standardization and eliminating barriers

1.1 Literature review of maturity aspects of the hydrogen economy in G20 countries

The key challenges in advancing the hydrogen economy in G20 countries are policy inconsistencies, the absence of a globally recognized hydrogen standard, inadequate infrastructure, high production costs, and limited technological progress. These obstacles impede the broader adoption and integration of hydrogen, which is essential for decarbonization and achieving net-zero goals.

Despite the significance of establishing hydrogen standards to facilitate international trade and the economy surrounding this resource, few studies evaluated the availability of national or international standards, as well as the status of legislative preparation or development in the world's leading economies. This study presents an in-depth literature review of existing research on the significance and impact of hydrogen legislation and standards. This study conducted a comprehensive literature search to ensure a thorough review of the relevant body of work. The search strategy included databases such as Google Scholar, ScienceDirect, Scopus, SpringerLink, etc., using keywords such as 'hydrogen legislation', 'hydrogen standard', 'green hydrogen challenges,' 'hydrogen policies,' etc. This research included studies published in high quality with a focus on peer-reviewed journal articles to ensure high-quality sources. The most recent studies are reviewed, covering various aspects of hydrogen legislation and standards, green energy policies, etc. This method allowed us to capture diverse perspectives and identify significant trends, gaps, and challenges in the field.

LaChance et al. [24] evaluated the development of risk-informed separation distances for hydrogen-related codes and standards. Their outcomes emphasized the importance of integrating risk assessment into regulatory frameworks to ensure safety while supporting the effective deployment of hydrogen technologies. San Marchi et al. [25] examined the research and development efforts, focusing on scientific progress that has supported the development of regulations, codes, and standards for hydrogen technologies across four essential areas. Key outcomes include an improved understanding of hydrogen's behaviour in storage and fuel cell applications, standardized testing methods for materials and components, and refined risk models to predict potential hazards. These advancements aid in developing reliable codes and standards, supporting the safe, widespread adoption of hydrogen technologies. Velazquez Abad and Dodds [26] conducted a comparison of the different definitions of GH2 found in the existing studies. They found major challenges involving the absence of universal definitions and standards, difficulties in verifying hydrogen's origin, and the need for reliable certification systems. Tackling these issues is crucial for fostering trust and expanding the green hydrogen market as a sustainable energy solution.

Jones et al. [27] assessed key priorities for EU hydrogen policy to enable a strong and sustainable hydrogen market. They highlighted the need for market incentives and funding mechanisms to support hydrogen adoption across sectors. They stressed the importance of developing cross-border infrastructure to foster a unified hydrogen market across the EU and call for collaboration among member states to ensure that regulatory frameworks align with the EU's carbon neutrality goals. Ringsgwandl et al. [28] provided an in-depth analysis of the regulatory and legislative challenges for green hydrogen production via electrolysis in Germany. They outlined how Germany's legal framework, including unbundling regulations, restricts electricity and natural gas operators from directly owning or managing hydrogen production facilities, complicating the integration of green hydrogen into the energy system. They noted that despite recent progress, further regulatory clarity is needed, especially regarding the eligibility of green hydrogen as a renewable energy carrier, to strengthen its competitive edge over fossil-based hydrogen in Germany's decarbonization efforts. A measurable criterion for assessing impurities in hydrogen fuel based on ISO 14687 is established by Lee et al. [29] which could prove valuable in assessing the conformity of H2 fuel at service stations with the quality requirements. They concluded that standardized reference materials and quality control measures are necessary to support hydrogen's role in clean energy, intending to reduce impurities and maintain performance standards in hydrogen-powered applications. The hydrogen standard in China is studied and assessed by Liu et al. [30]. They highlighted the importance of developing comprehensive standards to ensure the quality and sustainability of hydrogen production. They discussed the identification of criteria and methodologies for evaluating various types of hydrogen, which are intended to improve regulatory frameworks and facilitate the adoption of green hydrogen technologies in China's transition to a more sustainable energy system.

Talus and Martin [31] examined the evolving USA hydrogen legislation, highlighting recent federal and state initiatives to promote hydrogen as essential to a low-carbon energy future. They emphasized incentives like tax credits and subsidies supporting hydrogen infrastructure and use, particularly in challenging-to-decarbonize sectors. Key barriers, including infrastructure, regulatory, and safety issues, are also discussed, calling for stronger state-federal collaboration to create unified, sustainable hydrogen policies. Genovese et al. [32] offered a summary of hydrogen's safety to underscore the importance of adhering to hydrogen refuelling station regulations and standards. They emphasized the necessity of standardizing these guidelines to guarantee the safety, efficiency, and compatibility of hydrogen refuelling infrastructure. They also presented equipment details, safety assessments, and operational strategies. Bade and Tomomewo [33] examined the fragmented USA hydrogen regulatory landscape, pointing to gaps like the absence of national legislation, regional overregulation, inconsistent subsidies, and limited funding for hydrogen initiatives, all of which impact energy security and climate goals.

They emphasized the need for standardized national policies, coordinated subsidies, and stronger long-term funding commitments for hydrogen infrastructure. Bade et al. [34] reviewed the major economic, social, and regulatory challenges facing green hydrogen in the USA. They mentioned regulatory challenges stem from fragmented policies that lack national cohesion, making it difficult for green hydrogen to scale. They recommended a holistic approach combining technology advancements, supportive policy, and public engagement to establish green hydrogen as a viable energy solution. Inal [35] discussed hydrogen and fuel cell legislation in maritime decarbonization. It has been concluded that collaborative policy development among international maritime organizations to establish standardized safety protocols, emissions regulations, and incentives, aims to accelerate decarbonization in shipping.

Limited research has been conducted on hydrogen policy and its role within G20 countries. Görlach et al. [36] explored strategies for advancing green hydrogen development within G20 nations. They focus on policy recommendations to accelerate hydrogen adoption as a key component of sustainable energy transitions. They analyzed the current policy landscape, identified challenges hindering green hydrogen progress, and proposed actions to enhance cooperation among G20 countries. They presented insights into how targeted support, investment, and international collaboration could drive the green hydrogen agenda, positioning it as a catalyst for achieving global climate goals. Yalamati et al. [37] examined and compared the policies and geopolitical strategies of G20 nations concerning GH2, particularly in the context of achieving net-zero emissions. They assessed each G20 nation's approach to GH2 within the global shift to cleaner energy, focusing on policy frameworks, strategic priorities, and investment patterns. The study highlighted areas of potential collaboration or competition in the green hydrogen economy and identified gaps and challenges, providing insights for policymakers to strengthen hydrogen's role in sustainable energy transitions. Zulfhazli et al. [38] analyzed the prospective demand for hydrogen in the road transportation sector across 14 G20 countries. They examined factors influencing hydrogen adoption for vehicles, such as policy support, infrastructure development, and market readiness. Key outcomes include an assessment of projected hydrogen demand in each country, identification of drivers and barriers to hydrogen transition in transportation, and insights into strategies that can enhance hydrogen uptake. They presented valuable data for G20 policymakers and stakeholders working to promote hydrogen as a sustainable transportation alternative. Zulfhazli et al. [39] assessed the impact of deploying fuel cell vehicles on reducing greenhouse gas emissions in the road transport sector across 15 G20 countries through 2050. They modelled the potential emissions reductions achieved by replacing conventional vehicles with FCVs and evaluated the effectiveness of this shift in meeting climate targets. They provided data-driven guidance for policymakers aiming to reduce transport emissions with hydrogen-based solutions.

Some research has focused on the assessment of standard and policy of the energy sector. Williams et al. [40] evaluated the available net-zero energy building standards worldwide. They reported that a critical demand exists for a universally applicable zero energy standard on a global scale. They concluded that adopting an international zero-energy standard would promote clearer benchmarks, drive innovation in building technology, and accelerate the transition to more sustainable, energy-efficient building practices. Landner et al. [41] examined the link between legislation and investment in the electricity industry, noting that well-designed standards can incentivize further investment in the market. The study found that robust energy policies promoting flexibility options play a key role in strengthening grid stability, decreasing fossil fuel dependence, and facilitating greater integration of renewable energy sources. Roberts et al. [42] investigated how energy legislation influences organizational motivation to adopt sustainable practices. They concluded that effective legislation should balance strict standards with support mechanisms, like financial incentives and simplified compliance processes, to enhance organizational commitment to sustainable energy practices. Liu and Feng [43] studied the short and long-term influence of energy legislation on renewable energy across 129 countries worldwide. They identified the significant role of energy laws in fostering the promotion of renewable energy. They emphasized that robust legislative measures are essential for creating a supportive environment for renewable energy development, ultimately contributing to energy transition and sustainability goals.

Additionally, some other studies focus on assessing the hydrogen and clean energy transition within G20 countries. Mishra and Manhas [44] highlighted the G20's role in accelerating the global shift toward green energy, emphasizing collaborative strategies and policy frameworks. They argued that G20 can facilitate sustainable development goals by promoting innovation in renewable energy, such as solar, wind, and hydrogen, and by setting global benchmarks for energy efficiency. Otaki and Shaw [45] emphasized hydrogen energy's transformative potential in achieving a sustainable, low-carbon future, particularly within Asia's emerging economies. They mentioned strong regional collaboration and investment, noting that platforms like the G20 can catalyze unified policy efforts and promote shared resources to foster a robust hydrogen economy. They also found by addressing policy, investment, and sustainability gaps, G20 and other collaborative frameworks can support Asia and other regions in integrating hydrogen into their energy systems and improving resilience and energy security.

Salman et al. [46] examined the G20's strategic role in promoting carbon neutrality through international cooperation and technological advancement. They emphasized integrating the Paris Agreement's objectives into national and collective G20 policies to ensure alignment with global climate goals. They discussed how, by leveraging AI and prioritizing green energy investments, the G20 can accelerate pathways to carbon neutrality, foster global energy security, and create a more resilient, low-carbon global economy. Wang et al. [47] examined the environmental sustainability challenges within G20 countries, focusing on the impacts of economic growth, energy composition, foreign direct investment, and population dynamics. They highlighted that an overreliance on non-renewable energy within many G20 nations contributes substantially to this gap. They suggested that to close the sustainability gap, G20 economies must reconfigure their energy mix toward renewables, implement policies encouraging green foreign direct investment, and sustainably manage population growth. Wang et al. [48] explored how renewable energy adoption, economic complexity, and resilience to geopolitical risks influence environmental quality in G20 nations. They suggested that G20 countries prioritize diversifying their economies, increasing renewable energy use, and strengthening geopolitical resilience as critical strategies for enhancing sustainability and achieving long-term environmental quality.

The literature review encompasses both foundational and the latest research on hydrogen and sustainability pathways, with a focus on the influence of hydrogen and clean energy policies in G20 countries. This review reveals that previous studies have primarily addressed various facets of hydrogen legislation and standards, such as regulatory challenges, risks, and the impact of standards on low-carbon futures and decarbonization efforts. However, significant gaps remain. Most studies provide a broad overview of the hydrogen economy without targeting specific countries, and few delve into the existing hydrogen legislation and standards in leading nations within the hydrogen industry - a critical aspect for advancing hydrogen trade and economic frameworks.

Existing scientific and policy reports often lack comprehensive evaluations of hydrogen standards and legislation, both locally and internationally. Many studies on legislative frameworks concentrate on individual countries, limiting the ability to contextualize findings within the larger economic landscape of leading nations. Furthermore, the development and scope of hydrogen legislation and standards among G20 countries remain largely unexamined.

This study seeks to address these gaps by examining the available local and international hydrogen economy regulations in G20 nations to assess regulatory maturity and development levels. Prior research suggests that establishing a comprehensive, unified hydrogen standard could substantially advance various industry criteria. Furthermore, some studies highlight the role of clean energy policies and standards in enhancing sustainability across energy sectors, underscoring the critical importance of policy and regulatory frameworks. Consequently, this study targets the availability and evolution of hydrogen legislation as a core objective, intending to strengthen sustainability in the hydrogen economy and related energy sectors.

Other studies have focused on the G20's role in advancing environmental and economic sustainability, examining the challenges these countries face in the energy transition and providing recommendations for improvement. However, a major gap persists regarding hydrogen policy and the hydrogen economy: there is a lack of comprehensive studies that examine the current national hydrogen policies in G20 countries and their strategic plans for developing and promoting this industry at both local and global levels. To address this, this study not only assesses hydrogen legislation but also incorporates other dimensions of the hydrogen economy, providing a multi-faceted analysis. This study analyzes the comprehensive hydrogen policies and future plans of G20 nations using the most recent publications, organizational reports, and governmental documents that detail these countries' updated national strategies.

Financial availability is a critical driver in developing and expanding the hydrogen economy and trade. This study therefore includes an in-depth analysis of investment patterns, comparing financial commitments for hydrogen industry advancement across G20 nations - a dimension largely underexplored in previous research. Economic data were gathered from the most recent and officially approved allocations, covering multiple facets of the hydrogen economy, including supply chain development, infrastructure, technology promotion, research and development, and workforce expertise.

A distinctive feature of this study is the application of a maturity scoring approach based on various hydrogen economy criteria, employing the Weighted Scoring Model (WSM) methodology. This scoring model ranks the G20 countries in terms of their position, comprehensiveness, and maturity in hydrogen economy development - a novel assessment not previously explored in existing research. Each country is assigned a score reflecting the advancement and maturity of its hydrogen economy across defined criteria. To enhance the precision of this evaluation, each primary criterion is further divided into sub-criteria, enabling a detailed assessment based on these individual elements.

Overall, the dimensions and evaluations incorporated in this study represent areas that have been largely underexplored in previous research, underscoring the study's novelty across multiple criteria. These assessments distinguish this work from prior studies, addressing critical gaps in the understanding of hydrogen standards and the maturity of the hydrogen economy within G20 nations. This study provides important insights for policymakers, academics, and industry stakeholders, with the findings contributing to future research directions and supporting the global shift towards a sustainable hydrogen economy.

This work supports several United Nations Sustainable Development Goals (SDGs), notably SDG 7, which advocates for accessible, clean energy, and SDG 13, which emphasizes the need for urgent climate action. By examining the maturity and growth requirements of the hydrogen economy, this study contributes to the UN Climate Change Framework's goals by identifying key gaps and practical steps toward sustainable hydrogen implementation. These efforts focus on reducing emissions, promoting clean energy use, and advancing the global shift to low-carbon economies, highlighting hydrogen's potential to enhance climate resilience and sustainability.

Figure 1 illustrates various aspects of the hydrogen economy and industry. The net-zero strategy for all G20 countries is outlined in Table 1. The G20 group currently consists of 21 members, including 19 individual countries and 2 regional organizations: the European Union (EU) and the African Union (AU). These members represent a diverse range of economies, spanning multiple continents and encompassing both developed and emerging markets. It should be mentioned that the AU is excluded from this study due to limited data availability, and only South Africa has been assessed among AU nations. The following is a summary of the key criteria used to assess the maturity of the hydrogen economy in G20 countries:

Legislation/standard: This factor examines the presence and robustness of hydrogen-specific policies, regulations, and standards that provide a regulatory framework for hydrogen production, storage, and distribution. Legislation is crucial for ensuring safe, standardized practices and fostering market development.

Investment: Investment reflects the financial commitments made by both public and private sectors toward hydrogen projects. This includes funding for R&D, infrastructure development, and commercialization efforts, highlighting each country's commitment to advancing hydrogen technology.

Strategy/Future Plan: Strategy and plans encompass national roadmaps, targets, short and long-term goals that outline each country's vision for integrating hydrogen within its broader energy and decarbonization goals. These strategies often set the direction for policy, investment, and technological focus.

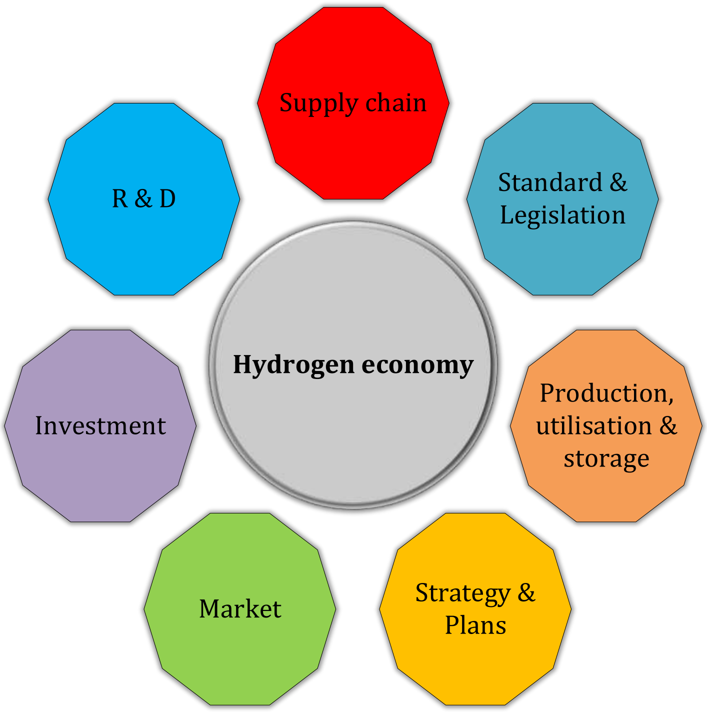

Fig. 1. Different aspect of sustainable hydrogen economy

Table 1. Net zero prospect in different countries

Country	Target	Country	Target	Country	Target	Country	Target
Argentina	2050	EU	2050	Italy	2050	South Africa	2050
Australia	2050	France	2050	Japan	2050	South Korea	2050
Brazil	2060	Germany	2045	Mexico	N/A	Turkey	2053
Canada	2050	India	2070	Russia	2060	UK	2050
China	2060	Indonesia	2060	Saudi Arabia	2060	USA	2050

2. G20 countries hydrogen economy

This section presents the country-by-country synthesis of the maturity of the hydrogen economy in G20 countries based on the criteria of legislation / standard, investment, technology /infrastructure / challenges, and strategy / future plan.

2.1. Argentina

2.1.1. Legislation

In 2006, Argentina enacted its first hydrogen legislation, marking a remarkable milestone. Presently, the Ministry of Productive Development is formulating a fresh regulatory framework that aligns with the sector's advancements over the past 15 years. The objective is to foster increased investments in the sector and emphasize the value of energy resources and technological capabilities. However, based on the available data, there is no comprehensive legislation and standard internationally accepted for hydrogen technology in Argentina. However, organizations such as the Ministry of Economics have stated that a regulatory framework should be developed to ensure stable investments over 30 years in Argentina. The Hydrogen Argentina platform, founded in 2020, advocates for developing clean hydrogen in the country. It highlights the importance of establishing a standardized framework for hydrogen technology. This standard would help position Argentina on the global hydrogen roadmap and attract substantial investments. This platform proposed that the standard should identify the differences between hydrogen originating from renewable energies and other sources [49].

2.1.2. Investment

The Ministry of Foreign Affairs of Argentina announced that Argentina and Japan have agreed to collaborate to develop GH2 production technology and use it as a pollutant-free fuel. This cooperation will help Argentina to develop its potential to integrate into a sustainable value chain [50]. It is projected that approximately US$ 8.4 billion will be invested in GH2 projects by 2028 [49]. A recent announcement disclosed that the European Union (EU) intends to invest approximately US$ 5.7 million in the production and commercialization of GH2 in Argentina. This investment is part of the EU's broader 30-million-euro fund, aimed at promoting the growth of Argentina's hydrogen market [51].

2.1.3. Technology/infrastructure developments

Argentina has one of the best wind energy sources in the World which can be applied as a low-carbon source of energy to generate GH2. It provides an excellent opportunity to develop infrastructure and facilities based on available resources and can be considered a sustainable energy source for hydrogen production [52]. Argentina possesses vast untapped potential in renewable resources, such as solar, wind, geothermal energy, and biomass. These resources can be harnessed effectively to produce GH2 [53].

2.1.4. Hydrogen strategy and future plan

The Argentine government, in conjunction with private and academic sectors, formulated the 2030 National Low-Emission Hydrogen Strategy in June 2022. The aim was to foster collaboration between the public and private sectors, encourage investments in science and technology, and promote industrial engagement, among other measures. These initiatives were designed to facilitate the implementation of hydrogen as a sustainable energy source. The strategy objective is to systematically arrange the required actions for the expansion of the hydrogen market in a progressive approach [52]. As per the government's projections, Argentina has the potential to generate over 1,000,000 tonnes of GH2 annually by 2030. Argentina aims to decrease the carbon footprint of its energy mix by substituting fossil fuels with GH2, particularly in the power generation industry. By pursuing these goals, Argentina intends to establish itself as a significant exporter of hydrogen and hydrogen-related technologies within the Latin American region. The 2030 strategy aims to drive development initiatives that are projected to create 50,000 job opportunities [52]. Anticipated innovations in sustainable energy are expected to create job opportunities and transform the current expertise in sustainability and renewable energy [54].

2.2. Australia

2.2.1. Legislation

The Australian government is planning to support the establishment of legislation internationally applicable for hydrogen and other energy certification. The government has signed some agreements to collaborate with other countries. For example, in January 2023, they signed an agreement with the Netherlands to collaborate on the development of standards and certification, supply chain expansion, trade policy, and logistics [55]. Australia adopted national standards and regulations regarding various aspects of hydrogen technology in July 2020. These standards cover areas such as safety, production technology (including electrolysis and fuel cells), storage, transportation, and fueling stations. To develop these standards, the Australian Hydrogen Council played a significant role. Some of these standards are adopted from international standards [56]. Department of Climate Change, Energy, the Environment and Water of Australia tries to improve the regulatory framework of the hydrogen industry through some supporting interventions such as [57]:

- Reviewing state and federal laws that impact hydrogen technology
- Determining regulatory challenges and obstacles in hydrogen projects
- Proposing solutions to address these challenges and recommending effective and transparent certification processes

2.2.2. Investment

The Australian Government has allocated more than AU$ 146 million (around US$ 95.9 million) towards initiatives related to hydrogen projects throughout the entire supply chain from 2015 to 2019 [57]. Australia has dedicated over AU$ 900 million (around US$ 591.3 million) toward developing the hydrogen. This commitment includes the establishment of multiple hydrogen hubs and the expanding a certification scheme that facilitates hydrogen trade [58]. According to The Australian Trade and Investment Commission (Austrade) report, the government is committed to investing over AUS$ 1.3 billion (around US$ 0.85) to develop hydrogen technology in Australia. Additionally, the government has allocated AUS$ 525 million (around US$ 344.9 million) to support hydrogen industrial hubs in Australia and AUS$ 89.5 billion (around US$ 58.8) for the development of highway and refuelling infrastructure. Furthermore, Australia is investing AUS$ 20 billion (around US$ 13.14 billion) to strengthen the grid network and boost battery production. Additionally, AUS$ 1.9 billion (around US$ 1.25 billion) will be allocated for the decarbonization of the industrial sector and the establishment of low-carbon factories. Furthermore, AUS$ 3 billion is being dedicated to the promotion of electrolysis and fuel cell technologies [55].

2.2.3. Hydrogen strategy and future plan

The Australian Government plans to perform a thoroughgoing examination of the National Hydrogen Strategy to ensure that Australia continues to progress as a prominent global hydrogen leader by 2030. This progress encompasses both the exportation of hydrogen and the decarbonization of industries within Australia. The Department of Climate Change, Energy, the Environment and Water will initiate a public consultation process in the near future to aid in the development of a revised strategy [57]. Australia's strategy is designed to take a flexible approach, focusing on initiatives that remove market barriers, facilitate the establishment of supply and demand, and improve global cost competitiveness. These measures will support the rapid scaling of operations as markets evolve.

Commonwealth Scientific and Industrial Research Organisation (CISRO) (which is a national science research agency in Australia), is attempting to create a hydrogen initiative that aims to collaborate with industry, government, and various research institutes. The goal of this initiative is to support R&D and demonstration projects. It aims to reduce risks, identify strategies to accelerate the hydrogen industry's development, and facilitate its industrial demonstration. Furthermore, this scheme aims to establish connections between Australian projects and international ones [57].

Australia faces two main challenges in becoming a global leader in the hydrogen industry: a limited workforce and a gap in skills and training. To address these issues, the government has committed to allocating AU$ 95.6 million (around US$ 62.8 billion) over nine years to create 10,000 energy apprenticeships. This initiative aims to cultivate a greener workforce, in line with the objectives of the National Hydrogen Strategy [59].

2.3. Brazil

2.3.1. Legislation

To date, Brazil has not established any official hydrogen standards that are globally applicable for production, storage, utilization, or transportation. However, in addition to preparing the National Hydrogen Program (PNH), some actions have been considered to improve regulations. These regulations, overseen by governmental agencies, address various aspects of hydrogen production, transportation, quality control, storage, and utilization. These actions include [60]:

- Analyzing the existing responsibilities and authorities of regulatory agencies, competent bodies, and entities, taking into account any potential new requirements that may arise
- Evaluating the necessity of formulating regulations for emerging technologies at the federal, state, and urban levels.
- Regulations monitoring to maintain flexibility in response to market dynamics and obstacle prevention
- Assessing the connections between various sectors and suggesting coordination
- Striving to create and implement codes, norms, and standards set by national organizations following global regulations
- Encouraging collaboration between governmental entities to regulate hydrogen, taking into account its diverse origins and applications, to achieve regulatory consistency
- Assessing the necessity of suggesting supplementary safety standards concerning hydrogen production, transportation, and utilization
- Evaluating the requirement to establish certification mechanisms for hydrogen, both in terms of its production and consumption.

2.3.2. Investment

The EU has pledged investments of € 2 billion (US$ 2.16 billion) in GH2 projects within Brazil [61]. Apart from various R&D projects and pilot plants, large-scale GH2 initiatives have been announced in Brazilian ports. These projects, currently under feasibility studies, involve investments totalling US$ 20 billion.

2.3.3. Hydrogen strategy and future plan

The Brazilian Hydrogen and Fuel Cell Systems Program, established in 2002 by the Ministry of Science, Technology, and Innovation (MCTI), is known as the Science, Technology, and Innovation Program for the Hydrogen Economy (ProH2). It was created to promote initiatives aimed at advancing hydrogen technology and fuel cell systems within Brazil. As a result, Brazil has become a leader in the research and development of hydrogen technologies within the Latin American region [62]. The National Hydrogen Program (PNH) was issued in July 2021 by the Ministry of Mines and Energy (MME). This program seeks to promote the growth and establishment of the hydrogen market in Brazil while also facilitating the country's international presence in a financially competitive manner [60]. The PNH2 consists of six main areas of focus [63]:

1. Strengthening research, development, and innovation and technological foundations
2. Enhancing capacity building and fostering the development of human capital
3. Energy planning initiatives
4. Establishing a legal and regulatory framework
5. Promoting market development and enhancing competitiveness
6. Fostering international partnerships and cooperation.

2.4. Canada

2.4.1. Legislation

The utilization of hydrogen is still in its initial phases across various sectors and jurisdictions in Canada. There are gaps in the current standards that must be addressed to facilitate widespread adoption. The absence of well-established and adopted standards in Canada pertaining to this specific end-use application is presently a significant factor impeding progress. Canada is actively collaborating with nations worldwide to establish and harmonize codes and standards. Initiatives like the Canada/USA Regulatory Cooperation Council are being pursued to facilitate this cooperation [64].

Around 200 experts have been gathered as a group named the Hydrogen Codes and Standards Working Group (CSWG). This group was formed to create standards and prepare legislation to facilitate the development and commercialization of hydrogen infrastructure and technology. This group includes diverse expertise from academia, industry, society, and government and has focused on three main pillars [65]:

- Considering various hydrogen generation ways from natural energy resources
- Storage and delivery of the generated hydrogen to various end users from the production site
- Covering utilization phase in different sectors (residential. Transportation, industry, and commercial)

2.4.2. Investment

In its 2023 Budget, the Government of Canada disclosed the CAD$ 5.6 billion (around US$ 4.02 billion) financial allocations in GH2. The budget also outlined the involvement of the Canada Growth Fund in facilitating the establishment of the country's GH2 [66]. The Government Budget for 2023 encompasses a provision of CAD$ 20 billion (around US$ 14.36 billion) in financial assistance for Clean Electricity investments. This support includes a minimum of CAD$ 10 billion (around US$ 7.18 billion) allocated to the Clean Power priority area and another minimum of CAD$ 10 billion (around US$ 7.18 billion) designated for the Green Infrastructure priority area [67].

2.4.3. Technology/infrastructure developments

Although certain hydrogen technologies have reached a commercially viable stage, ongoing support for R&D is essential. This support aims to further decrease costs, address less developed applications, and explore groundbreaking technologies for the sector's benefit. However, the limited duration of current funding cycles for R&D may restrict private sector investments in Canadian innovation. Therefore, bridging the policy gap lies in committing to long-term R&D support for advanced technologies [64].

Currently, many regions in Canada face limitations in terms of the availability of low-carbon-intensity hydrogen, which hampers the commercial and pilot implementation of end-use applications. Additionally, certain applications require the transportation and storage of hydrogen from production sites to the end-users, such as refuelling infrastructure for transportation purposes. It is crucial to synchronize the expansion of supply and distribution infrastructure with the increasing demand, but this coordination can be challenging and necessitates a localized development approach tailored to specific regions [64].

2.4.4. Hydrogen strategy and future plan

The Hydrogen Strategy for Canada provides a comprehensive roadmap detailing ambitious measures to position hydrogen as a pivotal enabler in achieving Canada's net-zero emissions goal by 2050. It also aims to position Canada as a prominent global leader in the production and utilization of clean renewable fuels. The strategy highlights that by 2050, the adoption of clean hydrogen can play a pivotal role in accomplishing Canada's net-zero objective. At the same time, it has the potential to create employment opportunities, drive economic growth, and protect the environment. Achieving this goal entails transitioning from conventional gasoline, diesel, and natural gas to zero-emission fuel sources. It involves capitalizing on evolving regulatory frameworks and embracing innovative technologies to provide Canadians with a broader range of zero-emission alternatives [64]. It is expected that Canada will achieve some benefits from this strategy including [64]:

- Igniting economic recovery while simultaneously expanding domestic production of low-carbon fuels to achieve long-term emission reduction goals. This presents distinctive prospects for Indigenous communities and businesses to participate and benefit from these endeavours.
- Strategically positioning Canada to emerge as a global leader in the supply of hydrogen technologies.
- Harnessing the power of hydrogen as a crucial catalyst to achieve the goal of net-zero emissions by 2050.
- Opening over 350,000 high-paying job positions at a national level.

According to a recent study, the export of hydrogen has the potential to reach CAD$ 50 billion (around US$ 35.89 billion) by 2050, thereby doubling the projected economic potential of the Canadian market within the same period. In November 2017, the Hydrogen Council projected that the worldwide annual sales of hydrogen and associated equipment could reach CAD$ 2.5 trillion (around US$ 1.79 trillion) by 2050. In a more recent estimate in September 2020, investment bank Goldman Sachs suggested that the market potential for hydrogen could amount to CAD$ 11.7 trillion (around US$ 8.4 trillion) by 2050, with significant shares allocated to Asia, Europe, and the United States [64].

2.5. China

2.5.1. Legislation

In December 2020, China released the "Standard and Evaluation of Low-carbon Hydrogen, Clean Hydrogen, and Renewable Hydrogen." This groundbreaking global initiative establishes the first official GH2 standard and offers calculation methodologies for assessing GHG emissions associated with diverse hydrogen production processes [30]. China has a larger number of national hydrogen standards than the International Electrotechnical Commission (IEC) and the International Organisation for Standardisation (ISO). Terminology, hydrogen fuel quality, safety precautions, building rules, production and purification methods, storage protocols, transportation and refueling regulations, applications, and testing procedures are only a few of the many topics covered by these standards [22].

Unincorporated technical organizations known as Standard Technical Committees play a pivotal role in developing national standards within specific fields. In the case of hydrogen, there are four primary national technical committees responsible for drafting such standards. The National Technical Committee of Hydrogen Energy (SAC/TC 309) specializes in standards related to hydrogen production, storage, transportation, fuelling, applications, testing, and safety. The National Technical Committee of Fuel Cell and Flow Battery (SAC/TC 342) focuses on standards on fuel cell terminology, stacks, and applications. The Subcommittee of Electric Vehicles of the National Technical Committee of Road Vehicles (SAC/TC 114/SC 27) is dedicated to fuel cell vehicle standards. Lastly, the Subcommittee of High-Pressure Vehicle Fuel Tanks of the National Technical Committee of Gas Cylinders (SAC/TC 31/SC 8) concentrates on standards for composite material cylinders, including high-pressure hydrogen cylinders for vehicles. Additionally, other national technical committees such as Gases, Work Safety, Metallic, and Non-metallic Coatings also contribute to the development of hydrogen-related national standards [22]. Based on previous study [22], the hydrogen standard framework in China is illustrated in Fig. 2.

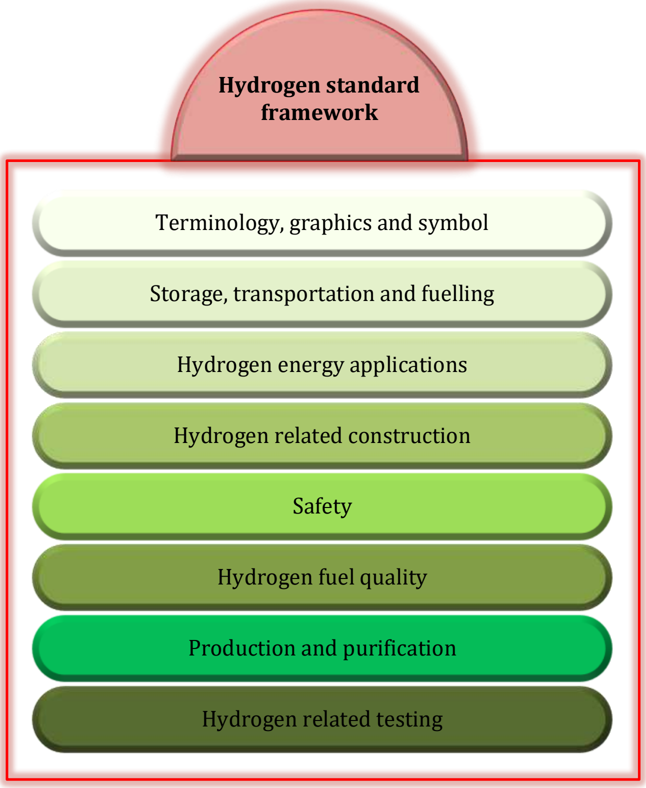

Fig. 2. Framework of the hydrogen standard in China

2.5.2. Investment

The exact amount of public funding, including funding from state-owned enterprises (SOEs), allocated to hydrogen projects in China, including GH2 initiatives, is not entirely transparent. However, a Chinese consulting firm has provided a more precise estimate, indicating that approximately 71.2 billion yuan (equivalent to US$ 10.33 billion) is invested annually in hydrogen projects [68].

2.5.3. Hydrogen strategy and future plan

Due to its ongoing swift industrialization and urbanization, China presently holds the position of the world's largest energy consumer [69]. The Chinese government has formulated a comprehensive medium- and long-term development blueprint for hydrogen spanning from 2021 to 2035. The plan outlines ambitious goals, including putting 50,000 hydrogen fuel-cell vehicles on the road and establishing a network of hydrogen refuelling stations by 2025. The strategy also aims to produce 100,000 to 200,000 tonnes of green hydrogen (GH2) per year by 2025, with renewable resources serving as the feedstock. It also intends to incorporate clean hydrogen into areas such as energy storage, electricity generation, and industrial. Notably, China is now known as the world's greatest producer and consumer of hydrogen [70]. China has emerged as the greatest global producer of hydrogen, producing roughly 33 million metric tons in 2021. The production scale is expected to increase even higher, reaching 43 million tons by 2030. According to the China Hydrogen Alliance, the percentage of GH2 in the energy mix is expected to rise dramatically, from 1% in 2019 to 10% by 2030. Furthermore, the market size is predicted to increase by nearly 30 times during this timeframe [71].

Currently, the main focus is integrating hydrogen energy into different energy systems and deploying it in high-impact sectors. Particular emphasis is placed on its application in public transportation. In the subsequent stage, the utilization of hydrogen will expand to encompass aviation, shipping, steelmaking, refineries, and the chemical industry. The ultimate progression of hydrogen deployment will involve its utilization in power generation and heating [72].

The transition of China to a hydrogen economy is accompanied by six primary challenges. These challenges include the absence of crucial technologies, incomplete standards, and specifications, high costs and insufficient infrastructure, geographic disparities in resources and demands, unclear public acceptance, and a dearth of supportive policies [73].

2.6. European Union (EU)

2.6.1. Legislation

In October 2021, the European Clean Hydrogen Alliance issued a report identifying the lack of hydrogen standards as a major barrier to the broad adoption of hydrogen technologies and applications. As a result, the alliance created a specialized Working Group focused on hydrogen standardization. The roadmap for hydrogen standardization has been released by the European Clean Hydrogen Alliance. This roadmap addresses the standardization requirements for the complete hydrogen value chain, encompassing production, distribution, transport, storage, and end-use applications. The Working Group on Standardization has been assigned the following responsibilities: (I) Identifying and addressing issues, gaps, challenges, and priorities within the existing standardization framework throughout the entire hydrogen value chain and (II) creating a roadmap for further development and implementation of hydrogen standardization initiatives [74]. Standards are formulated through collaborative efforts involving various stakeholders, including manufacturers, consumers, and regulators of specific materials, products, processes, or services. Together, they reach a consensus on shared specifications and procedures that address business requirements, fulfill consumer expectations, and ensure satisfactory levels of public safety [74].

2.6.2. Investment

Based on the European Commission report, until 2030, investments in electrolyzers could vary from € 24 to € 42 billion (around US$ 25.56 to 4.72 billion). Additionally, during the same timeframe, an estimated € 220-340 billion (around US$ 234.26 to 362 billion) will be necessary to expand and directly link 80-120 GW of solar and wind energy production capacity to the electrolyzers, ensuring a sufficient electricity supply. The cost of retrofitting approximately half of the existing plants with carbon capture and storage is projected to be around € 11 billion (around US$ 11.71 billion). Furthermore, an investment of € 65 billion (around US$ 69.2 billion) will be necessary to develop hydrogen transport and distribution infrastructure, storage facilities, and hydrogen refueling stations. Looking ahead to 2050, the EU would need to invest an estimated € 180-470 billion (around US$ 191.67-500.47 billion) in production capacities to meet hydrogen demands. Lastly, substantial investments will be necessary to adapt end-use sectors for hydrogen consumption and the adoption of hydrogen-based fuels. For instance, converting a standard EU steel installation reaching the end of its lifecycle to hydrogen could cost around € 160-200 million (around US$ 170.37-212.96 million). In the road transport sector, expanding the number of small-scale hydrogen refuelling stations by 400 units might require investments of € 850-1000 million (around US$ 905.1-1064.82 million) [75].

2.6.3. Challenges

Nonetheless, the implementation of hydrogen technology in Europe encounters significant hurdles that neither the private sector nor individual Member States can tackle in isolation. Successfully advancing hydrogen development beyond a critical phase requires substantial investment and a supportive regulatory framework. It also depends on the emergence of lead markets, ongoing research, and innovation to discover transformative technologies. Additionally, bringing new solutions to market is essential. Additionally, the establishment of a large-scale infrastructure network is essential to overcoming these challenges. Only the EU and its single market can facilitate this development effectively. Collaboration with third-country partners is also a crucial component in addressing these obstacles [75].

2.6.4. Hydrogen strategy and future plan

The EU has introduced a holistic framework through its hydrogen strategy and REPowerEU initiative, aiming to promote the adoption of renewable and low-carbon hydrogen. This comprehensive approach seeks to effectively reduce carbon emissions in the EU and lessen its reliance on imported fossil fuels while ensuring economic viability. In 2020, the EU adopted the hydrogen strategy (COM/2020/301), which introduced targeted policy measures across five key areas. These areas include providing financial support for investments and promoting both production and demand. Additionally, the strategy focuses on establishing a hydrogen market and infrastructure, fostering research and collaboration, and strengthening international cooperation [76].

The EU's primary focus is on advancing renewable hydrogen, primarily derived from wind and solar energy sources. This emphasis on renewable hydrogen aligns best with the EU's long-term objectives of achieving climate neutrality and zero pollution. Furthermore, it is the most consistent choice within an integrated energy system approach. In the short and medium run, alternative varieties of low-carbon hydrogen are essential. Their primary purpose is to swiftly curtail emissions from current hydrogen production and facilitate the simultaneous adoption of renewable hydrogen, both in the present and the future [75].

During the initial phase spanning from 2020 to 2024, the key strategic goal is to implement a minimum of 6 GW of renewable hydrogen electrolyzers within the EU. Additionally, this phase aims to produce up to 1 million tonnes of renewable hydrogen to effectively decarbonize the current hydrogen production processes. During the second phase, which spans from 2025 to 2030, the vision is to fully integrate hydrogen into the EU's integrated energy system. This includes the ambitious goal of installing at least 40 GW of renewable hydrogen electrolyzers by 2030. Additionally, it aims to produce up to 10 million tonnes of renewable hydrogen within the EU by this target year. In the third phase, starting from 2030 and progressing towards 2050, renewable hydrogen technologies are expected to reach full maturity and be widely implemented on a large scale. The primary objective during this period is to target the hard-to-decarbonize sectors where other alternatives may not be viable or prove to be more costly [75].

In 2022, hydrogen made up less than 2% of Europe's energy consumption, primarily serving the production of chemical goods like plastics and fertilizers. Unfortunately, 96% of this hydrogen came from natural gas, leading to substantial CO_2 emissions. To address this, the European Commission has set ambitious goals of generating 10 million tonnes of renewable hydrogen and importing an additional 10 million tonnes by the year 2030 [76].

2.7. France

2.7.1. Legislation

The legal framework governing hydrogen is established in Law-Decree No. 2021-167 dated 17th February 2021. The main purpose of this law is to define and categorize the various legal classifications of hydrogen. It also aims to establish protocols for tracking hydrogen within networks and to create public support mechanisms to drive growth in the hydrogen sector. Nevertheless, the publication of the implementing regulations for the Law Decree is still pending [77]. The regulations governing the production of hydrogen, and the construction of fuelling stations are applicable under the regulations for environmentally classified facilities (ICPE). Currently, there are no dedicated regulations in place for the transportation, import, and export of hydrogen [77].

2.7.2. Investment

France's government planned to provide € 7.2 billion (around US$ 7.67 billion) of public investment towards the development of decarbonized hydrogen by 2030. This includes € 2 billion (around US$ 2.13 billion) between 2020 and 2022 and € 3.4 billion (around US$ 3.62 billion) by 2023 [78]. Based on the IEA report, France has allocated an extra € 1.9 billion (around US$ 2.02 billion) for the advancement of decarbonized hydrogen technologies by 2030, aligning with its objective to lead in GH2 production and achieve decarbonization in the industrial sector [79].

2.7.3. Hydrogen strategy and future plan

As early as 2018, France emerged as one of the pioneering nations to initiate a comprehensive national hydrogen program. In September 2020, the Ministry of the Ecological Transition unveiled a national strategy focusing on the advancement of decarbonized and renewable hydrogen in France. The strategy outlines three primary focal areas [80]:

- Growing the electrolysis technology for industrial decarbonisation
- Expanding the decarbonized hydrogen utilization in the field of heavy-duty transportation
- Enhancing the R&D and skill to foster the adoption of future hydrogen applications

2.8. Germany

2.8.1. Legislation

The majority of the applicable regulations pertaining to hydrogen and fuel cells in Germany presently rely on or need to be adjusted according to European legislation [21]. The existing legal and regulatory framework for hydrogen is still lacking in comprehensiveness. Based on the Clean Energy Wire report in February 2021, the German government has recently sanctioned new legislation to regulate the developing hydrogen network infrastructure. Under this legislation, the existing gas pipeline network and the new hydrogen infrastructure will be regulated separately [81].

2.8.2. Investment

The German government is planning to invest around € 550 million (around US$ 586.1 million) in new hydrogen infrastructure establishment [82]. A total of € 7 billion (around US$ 7.46 billion) in investments have been designated specifically for the development of GH2 by the German government [83].

2.8.3. Hydrogen strategy and future plan

To promote the adoption of environmentally friendly hydrogen technologies, the German Federal Government has devised a National Hydrogen Strategy. This strategy includes various aspects of hydrogen technology such as transportation, production, heat, infrastructure, R&D and innovation, and international markets and collaborations. The main purposes of this strategy are [84]:

- Diminishing GHG emissions through developing renewable-based hydrogen production and its associated products as fundamental components of the energy transition
- Focusing on a domestic market expansion by developing suitable hydrogen production capabilities
- Formulating a regulatory framework that facilitates the development and expansion of the essential transport and distribution infrastructure required for hydrogen
- Enhancing the competitiveness of German companies by fostering the adoption, R&D, and hydrogen technologies export
- Ensuring a sustainable and reliable supply of renewable hydrogen and its derived products is a priority, which can be achieved through international partnerships.

Germany has outlined its plans to establish a production capacity of 5 GW by the year 2030, with an additional capacity of 5 GW set to be constructed between 2035 and 2040 [83].

2.9. India

2.9.1. Legislation

There is no internationally recognized hydrogen technology standard in India. A webinar was held in April 2023, bringing together the International Solar Alliance (ISA), the Green Hydrogen Organisation India (GH2 India), the Indian Energy Storage Alliance (IESA), and the Global Wind Energy Council India to facilitate the rapid advancement of GH2 standards and certification in India through collaborative discussions.

2.9.2. Investment

Under the GH2 mission, the Indian government has recently reported an initial financial expenditure of roughly US$ 2.5 billion [85] of which US$ 53 million will be allocated to R&D and US$ 197 million to pilot projects [86]. It is estimated that more than € 90 billion (around US$ 95.9 billion) will be invested in GH2 by 2030 [87].

2.9.3. Hydrogen strategy and future plan

The Ministry of Power launched the initial phase of the national GH2 policy on February 17, 2022, with a focus on advancing research, developing infrastructure, and stimulating demand for green hydrogen. [87]. India has set lofty goals, including achieving energy independence by 2047 and reaching net zero emissions by 2070. The hydrogen mission plan is predicted to have some outcomes by 2030 such as creating new jobs, investing more in hydrogen development, and establishing a minimum annual production capacity of 5 million metric tonnes (MMT) for GH2, alongside the addition of approximately 125 gigawatts of renewable energy capacity, annually around 50 MMT GHG emissions abatement, and diminishing the fossil fuel import (€ 11.4 billion by 2030) (around US$ 5.33 billion) [88]. In a recent development, the Indian cabinet granted approval to the National Green Hydrogen Mission on January 5th, 2023. The mission's primary objective is to position India as a prominent global producer and provider of GH2. Also, India has projected the creation of around 600000 jobs by 2030 in the GH2 economy [87].

2.10. Indonesia

2.10.1. Legislation

There are no laws or standards for hydrogen technology in Indonesia. According to Hydrogen Business Desk (HBD), Indonesia needs innovative and comprehensive energy regulations to facilitate the construction and development of renewable energy infrastructure. The Indonesian government has begun rewriting and establishing an updated regulation for sustainable energy technology [89].

2.10.2. Investment

There are several factors that investors have major challenges to securing funding for clean energy projects in Indonesia like elevated interest rates, ineffective policy schemes, and restricted availability of long-term debt financing [89]. However, some agreements have been made to generate GH2 in Indonesia. Samsung and Hyundai recently announced their partnership with the Global Green Growth Institute on a project costing US$ 1.2 billion to generate GH2 using geothermal electricity in North Sumatra [90]. The Indonesian government anticipates requiring private sector investments totalling US$ 25.2 billion between 2031 and 2060 to foster the development of GH2 [91].

2.20.3. Hydrogen strategy and future plan

Ensuring a reliable energy source is a critical element in fostering the development of Indonesia [92]. The Indonesian government predicted that for GH2 development between 2031 and 2060, a $25.2 billion investment from the private sector will be needed. Pertamina has committed to investing $11 billion towards GH2 as a part of its green energy objectives [93]. Indonesia has determined that CO_2 emissions diminish through hydrogen technology application for each decade (for instance, 796, 956, and 1526 million tonnes of CO_2 reduction for the 2036-2040, 2041-2050, and 2051-2060 periods) [93]. According to projections, Indonesia will require approximately 4 million tonnes per year of blue and green hydrogen production by 2025, which will be twice by 2030, and approximately 17 million tonnes by 2040 [89]. Up to now, many countries have drafted their national hydrogen strategy; however, Indonesia has not defined any hydrogen development roadmap yet [94].

2.11. Italy

2.11.1. Legislation

There are some national regulations regarding different aspects of hydrogen technology. In October 2018, the Ministry of Interior Affairs, together with the Ministry of Infrastructures and Transport, issued updated technical regulations aimed at fire prevention. These regulations specifically apply to the design, construction, and operation of hydrogen distribution facilities for automotive vehicles. The update revised the earlier regulations from 2006, overcoming previous technical development challenges. This is the only available legislation for hydrogen generation and operations. Furthermore, to produce hydrogen through reforming or electrolysis, obtaining Integrated Environmental Authorization from the Ministry of the Environment and Protection of Land and Sea is required. However, there are currently no regulations in place regarding the connection of hydrogen generator systems with the grid network. Due to the absence of specific national regulations regarding hydrogen transportation, Italy has adopted the latest European ADR (Accord for the Transport of Dangerous Goods by Road) regulation. This regulation encompasses the guidelines for the international transportation of hazardous materials by road. Hydrogen, being classified as a flammable gas, is included among the hazardous materials covered by these regulations [95]. However, there is no comprehensive legislation and standard regarding hydrogen technology internationally applicable in Italy that comprises all hydrogen market edges.

2.11.2. Investment

The National Recovery and Resilience Plan (NRRP) has earmarked around € 3 billion (around US$ 3.2 billion) to enhance hydrogen technology in Italy for use in R&D and the development of hydrogen utilization in transportation and industry [95]. Moreover, the European Commission has recently approved an Italian plan worth € 450 million (around US$ 479.5 million) aimed at producing GH2 [96]. According to the Italian Ministry of Economic Development, they have set a target of investing approximately € 10 billion (around US$ 10.7 billion) in GH2 production by 2030. Half of this amount is expected to be sourced from European funds and private investments [97].

2.11.3. Hydrogen strategy and future plan

Italian Ministry of Economic Development in November 2020 published the "Hydrogen Strategy," which outlined preliminary guidelines for Italy's approach to hydrogen. The document considered both short-term and long-term goals, aiming for 2% of national energy consumption to be derived from hydrogen by 2030 and 20% by 2050. This strategy is planned to consider key sectors including chemicals, public transportation, and refining crucial areas for the utilization and advancement of hydrogen [95]. The Ministry anticipates achieving a reduction of approximately 8 million tons of CO_2 equivalent in emissions by 2030, along with the creation of up to 10,000 permanent jobs in the medium term [98].

2.12. Japan

2.12.1. Legislation

There are no specific regulations in place regarding the utilization of hydrogen. Instead, hydrogen is currently governed under the category of high-pressure gas. The High-Pressure Gas Safety Act is the primary legislation overseeing the safety aspects of high-pressure gases, including hydrogen. Consequently, obtaining permission from or notifying the prefectural governor is necessary for manufacturing and/or hydrogen storage, and the specific requirements depend on the quantity of production and/or storage involved. Moreover, hydrogen transportation must adhere to the technical standards mandated by the High-Pressure Gas Safety Act. However, several other regulations, including those pertaining to construction and the environment, are also relevant [99].

2.12.2. Investment

Prime Minister of Japan announced that the supply capacity of hydrogen will expand to 12 million tons by 2040 due to strong global competition and fuel demand. Japan also plans to enhance the hydrogen supply chain. They will also invest around US$ 113 billion over the next 15 years in the development of hydrogen technologies [100].

2.12.3. Hydrogen strategy and future plan

Japan is investigating hydrogen uses in a variety of areas, including transportation, power generation, and manufacturing, as part of an economic decarbonization strategy. Several challenges need to be overcome to expand the use of hydrogen as an energy source. For example, hydrogen can be expanded for use in trains, ships, trucks, and other modes of transportation. Furthermore, to make hydrogen an inexpensive resource, a worldwide supply chain system must be combined with the Japanese storage infrastructure [101].

The Japanese government is planning to develop a broad international hydrogen supply chain to reduce hydrogen costs by 2030. Additionally, it aims to create incentives to apply ammonia for power production. The Ministry of Economy, Trade and Industry of Japan (METI) adjusted the first national hydrogen scheme in 2017 named basic strategy, followed by Strategic Roadmap for Hydrogen and Fuel Cell named strategic roadmap which was issued in 2019. These two strategies create a practical framework to develop a hydrogen economy in Japan comprising the following goals [102]:

- Hydrogen supply chain improvement
- Hydrogen generation cost decrease

- Increasing the transportation and storage capacity of hydrogen
- Consumer expansion of hydrogen and ammonia

In these frameworks, they will seek to reduce the hydrogen cost as much as possible competitive with other energy sources (20-30 JPY/Nm3) (around US$ 0.13-0.2 JPY/Nm3), also declining the technology costs (for instance, electrolyser cost by 75%). In addition, allocating financial resources for R&D to hydrogen and ammonia usage commercialisation as fuel by 2030 and increasing the number of fuel cell vehicles and hydrogen refuelling stations are other main goals of these plans [102].

2.13. Mexico

2.13.1. Legislation

Mexico lacks a comprehensive and coherent framework that adequately encompasses the hydrogen value chain. The Mexican Constitution does not specifically address or regulate hydrogen technology and transportation. In Mexico, there is no dedicated regulatory authority tasked with the regulation of hydrogen projects [103]. The incorporation of hydrogen as an alternative energy source has faced limitations in Mexico due to the absence of regulations concerning storage, applications, and safety guidelines [104].

2.13.2. Investment

The financing of hydrogen projects in Mexico, whether from the public or private sectors, faces significant challenges primarily due to the absence of dedicated funding options. Also, the negative anticipation of Mexico's economy causes insecurity in hydrogen infrastructure investment [103]. It is projected that cumulative investments reaching approximately US$ 8.5 billion by 2050 will be allocated to meet the hydrogen demand for heavy-duty fuel cell electric vehicles in Mexico [105]. According to the founder and president of the Mexican Hydrogen Association, GH2 projects in Mexico have planned investments of approximately US$ 1.35 billion, and the potential for further growth in this sector is substantial [106].

2.13.3. Hydrogen strategy and future plan

Hydrogen utilization and regulation in Mexico are limited, both in terms of the regulatory framework and project implementation. Mexico, like other countries dealing with energy transition concerns, has always chosen a more scientific rather than practical approach. However, The Mexican Hydrogen Association has been established to facilitate the improvement of the hydrogen industry in Mexico through effective strategies and actions. The main objectives of this association are [107]:

- Promoting awareness about the challenges related to hydrogen
- Engaging all relevant stakeholders from the public and private sectors who play an effective role in developing the hydrogen industry
- Contributing to evaluating the hydrogen landscape in Mexico, including identifying the potential, opportunities, and challenges
- Expanding collaboration with national and international organizations on hydrogen projects

Palacios et al. [108] reported that Mexico's efforts in implementing hydrogen have been insufficient thus far. Therefore, it is crucial to establish a comprehensive and well-organized strategy that outlines the approach and steps for hydrogen implementation in the country. In Mexico, it is important to promote strategies, research, implementation plans, and public incentives to ensure a prosperous transition to hydrogen-based clean energy sources [108]. It should be noted that, due to Mexico's geological situation, the country has a high potential for hydrogen production using various resources.

2.14. Russia

2.14.1. Legislation

Based on the available resources, there is currently a lack of established standards and legislation specifically addressing hydrogen technology in Russia.

2.14.2. Investment

To become a significant exporter of low-carbon hydrogen, the Russian government plans to invest 9.3 billion Roubles (around US$ 125 million) by the end of 2024 in developing its emerging clean hydrogen sector [109].

2.14.3. Hydrogen strategy and future plan

The Energy Strategy 2035 was endorsed by the Russian government on June 9, 2020. The strategy outlines the following objectives [110]:

- Achieving a 5-9% growth in energy production by 2024, relative to the levels observed in 2018,
- Boosting fuels and energy resources exports by 9-15%,
- Enhancing investments in the energy sector by 1.35-1.4 times, and
- Raising Russia's gasification level from 68.6% to 74.7% by 2024 and to 82.9% by 2035.

An official directive from the Russian government regarding hydrogen policy was issued on April 5, 2021, outlining the country's plans for the development of the hydrogen economy from 2024 to 2050. This order complements Russia's Energy Strategy 2035 and establishes a comprehensive long-term roadmap for the hydrogen sector until 2050. The Energy Strategy 2035 emphasizes the significance of energy-related innovative technologies, particularly hybrid and electric vehicles, including those powered by hydrogen. By late July 2020, the Russian Ministry of Energy formulated a roadmap outlining Russia's plans for hydrogen energy development between 2020 and 2024. This roadmap was submitted to the federal government and includes a range of measures. These measures involve supporting pilot projects in the production sector, improving the regulatory framework, and refining technology regulations related to hydrogen production, transportation, storage, and utilization [110]. Based on the analysis conducted by the Energy Research Institute of the Russian Academy of Sciences, it can be inferred that in the near future until 2035, the most favourable options for Russia would be the export of blue hydrogen, produced through methane steam conversion with carbon capture and storage [111].

2.15. Saudi Arabia

2.15.1. Legislation

Saudi Arabia does not currently have any special legislation in place to support hydrogen projects [112]. However, a technical regulation for hydrogen vehicles has been issued. The goal of this Technical Regulation is to specify the essential safety criteria for hydrogen-powered vehicles that come within its scope. It also intends to establish the conformity assessment procedures that suppliers must follow to preserve the environment, as well as the health and safety of consumers and drivers [113].

2.15.2. Investment

Saudi Arabia is looking to promote economic security by investing in hydrogen technology. US$ 36 billion is planned to invest in hydrogen technology in Saudi Arabia by 2030. They are hopeful to absorb more money based on their national hydrogen strategy. Ministry of Energy mentioned that their focus would be on principal factors of the value chain comprising production, export potential, and hydrogen application in domestic, transportation, and industrial sectors.

2.15.3. Hydrogen strategy and future plan

Reports indicate that Saudi Arabia is currently developing an official strategy for hydrogen. The country is aiming to position itself as the global leader in hydrogen production. With plans to produce 2.9 million tons of clean hydrogen annually by 2030 and 4 million tons by 2035, Saudi Arabia is prioritizing a significant market share in blue hydrogen, particularly through the production of blue ammonia [114].

2.16. South Africa

2.16.1. Legislation

Based on the available reports and information, no specific standards or legislation for hydrogen technology has been found in South Africa.

2.16.2. Investment

South Africa's Department of Environmental Affairs (DEA) has introduced a Green Fund, supported by government resources, to support the transition toward a low-carbon development pathway, including hydrogen initiatives. Approximately ZAR 800 million (around US$ 44.6 million) has been allocated to this initiative [115]. The German development bank, KfW, has launched a program worth € 200 million (around US$ 213.1 million) aimed at providing support for the development of GH2 projects in South Africa [116].

2.16.3. Hydrogen strategy and future plan

The Hydrogen Society Roadmap, released by the Department of Science and Innovation in South Africa, establishes a framework for prioritizing the implementation of the hydrogen economy at a national level. This strategy seeks some outcomes such as [117]:

- Developing a market for South African GH2 with the aim of facilitating exports
- Heavy-duty transportation decarbonization
- Energy-intensive sectors' decarbonization
- Promoting the expanded utilization of various forms of hydrogen (grey, blue, turquoise, and green) within the energy network, aligning with the shifting towards a net-zero plan. Establishing a specialized centre for manufacturing hydrogen and fuel cell equipment.

As part of the roadmap, the targets include the deployment of 10 GW of electrolysis and a minimum annual hydrogen production of 500 kt by 2030, with an increase to 15 GW capacity by 2040. In the short term, the emphasis is on the transport sector and showcasing industrial technologies, while the long-term vision involves sector coupling and the utilization of hydrogen in the power sector. It has been expected that these initiatives have the potential to generate over 30,000 job opportunities each year by 2040 [117].

2.17. South Korea

2.17.1. Legislation

There is local legislation about any gaseous fuels that should be produced in South Korea. This license should be obtained from the mayor or local government. Also, based on the Hydrogen Act scheme, the companies that intend to manufacture fuel cells or hydrogen-related devices must have the local authorities' approval. Importer companies to South Korea should register their business in the Ministry of Energy platform. Besides, the importing of hydrogen-based technologies is legislated should be monitored by the Ministry of Energy according to the Hydrogen Act [118].

The main organization of legislation preparation in South Korea for any energy technologies comprising hydrogen is the Ministry of Energy. In addition, an organization named the Hydrogen Economy Committee should be established to ensure the implementation of the Ministry of Energy policies properly. This committee consists of seven other members from the government sector, and experts [118].

The main hydrogen producers in South Korea are generating grey hydrogen that is based on fossil fuel applications. According to the Ministry of Trade, Industry, and Energy of South Korea website, the prime minister announced the new hydrogen economic policy pathway in the 5th Hydrogen Economic Commission meeting. Three main promotion plans named '3UP' have been defined which are Scale-Up, Build-Up, and Level-UP [119].

- The Scale-Up approach follows the path to developing the clean hydrogen ecosystem by appointing a global supply chain and establishing a large-scale hydrogen requisition from transportation and power production prospects.
- The Build-Up strategy aims to construct a legitimate framework to improve the distribution facilities and promote the clean hydrogen application.
- The Level-Up plans are related to innovating activities and technical improvement to place South Korea as a leader in hydrogen technology (such as electrolysis, and hydrogen-based turbines) in the World.

Also, some regulation has been defined for hydrogen transportation based on the High-Pressure Gas Safety Control Act which states that dangerous gausses transportation like hydrogen should be done via tube trailers and specialized pipes [118].

2.17.2. Investment

According to the Hydrogen Act plan, the government of South Korea provides loans and subsidies to expand projects related to hydrogen technology. The government has a plan to allocate US$ 34 million in financial resources as well as enhance the maximum restriction of loans for companies that work on hydrogen technology promotion. To be eligible for this funding is dependent on the company's determination to specialize in hydrogen, invest 20% of its R&D policy in hydrogen development, and sell a minimum of 30% of hydrogen-based products [62].

In 2019, the Hydrogen Energy Network (HyNet) was established with an initial investment of US$ 119 million. The purpose of HyNet is to enhance the infrastructure for hydrogen fuelling. The plan is to expand the existing fleet of approximately two dozen Hydrogen Refuelling Stations to 310 by 2022 and further to 1,200 by 2040 [120]. In the year 2021, the South Korean government allocated approximately US$ 702 million for hydrogen projects. Additionally, they have already pledged an additional US$ 2.3 billion to develop a hydrogen-powered fuel cell electric vehicle market through public-private partnerships by the end of 2022 [121]. In 2021, five major South Korean conglomerates made a collective announcement about their intentions to invest more than US$ 38 billion in the hydrogen economy by the year 2030 [122].

2.17.3. Hydrogen strategy and future plan

Korea presented its Hydrogen Economy Roadmap in January 2019, outlining several ambitious ambitions. The program aims to produce 6.2 million fuel cell electric vehicles and create at least 1,200 refueling stations by 2040. It also outlines plans to put at least 35 hydrogen buses on the road in 2019, with the number progressively increasing to 2,000 by 2022 and 41,000 by 2040. Furthermore, the roadmap seeks to increase the energy sector's fuel cell power generation capacity to 15 GW by 2040 [123].

2.18. Turkey

2.18.1. Legislation

Turkey has not set any regulations regarding hydrogen technology. It should be noted that an ambiguous part in a specific resolution of renewable energy infrastructure named 'solar/hydrogen' in the Energy Market Regulatory Authority of Turkey (EMRA), yet there is a gap in hydrogen regulation in a significant way. There are several ongoing attempts including academic partners, companies, and international partners to develop incomplete standards to develop the hydrogen application in the future [124].

The Ministry of Industry and Technology of Turkey has applied mirroring legislation adopted from the EU to regulate hydrogen-based and mixed-fuel vehicles to predict trade and traffic. Additionally, according to regulations issued by the Ministry of Energy and Natural Resources of Turkey (MENR) in 2011, which aim to improve the efficiency and application of energy systems, further research and development (R&D) efforts are needed. These studies should focus on hydrogen systems utilizing renewable technologies and work towards making hydrogen generation more cost-effective [124].

2.18.2. Investment

Within a span of approximately eleven years, Turkey has multiplied its operational renewable energy capacity by three, reaching a level of roughly 45 gigawatts. Additionally, the country has dedicated an investment of nearly US$ 40 billion towards renewable energy initiatives [124].

2.18.3. Hydrogen strategy and future plan

Since 2020, the MENR has started developing a hydrogen roadmap including market expansion and applying guidelines for a national hydrogen strategy. The short-term hydrogen strategy has been defined as [124]:

- Applying local coal to generate hydrogen
- Heating decarbonisation
- Developing renewable power generation
- Enhancing the incentive of boron usage for hydrogen storage and conservation

In addition, as part of the Turkish national energy plan, the Ministry of Energy and Natural Resources in Turkey has delineated its intentions to enhance the flexibility of the electrical grid. One of the key strategies is to augment the electrolyzer capacity to 5 GW by 2035 [125]. According to Amil and Yılmazoglu [126] assessment, it is certain that Turkey must allocate resources to hydrogen technologies and enhance the proportion of domestically produced renewable energy technologies by 2030.

2.19. United Kingdom (UK)

2.19.1. Legislation

The UK Low Carbon Hydrogen Standard (LCHS) establishes the criteria for determining 'low carbon hydrogen' during the production phase, supporting the implementation of both the UK Hydrogen Strategy and Energy Security Strategy. The standard provides a comprehensive outline of the methodology to calculate emissions related to hydrogen production and the specific obligations producers must fulfill to demonstrate compliance with the low-carbon criteria. The purpose of the standard is to ensure that government-supported low-carbon hydrogen production directly contributes to meeting GHG emission reduction targets as mandated by the Climate Change Act. Based on this law, producers of low-carbon hydrogen must show compliance with the standard by reporting a GHG emissions intensity of 20 gCO2e/MJLHV (grams of CO2 equivalent per megajoule of lower heating value) or lower for the hydrogen they produce. This standard outlines the method for calculating GHG emissions linked to the production of low-carbon hydrogen specifically within the UK [127].

2.19.2. Challenges

Several strategic obstacles throughout the value chain must be addressed to enable large-scale production and utilization of hydrogen in the UK, such as [128]:

- The higher hydrogen cost compared to conventional high-carbon fuels.
- Uncertainty in the technological part
- Uncertainty in regulation and policy
- Infrastructure development and adaptation
- Requiring coordination between supply and demand

2.19.3. Technology/infrastructure developments

The UK possesses extensive expertise in the manufacturing, distribution, preservation, utilization, and oversight of gas, specifically natural gas. This extensive utilization of natural gas for powering industries, households, and generating electricity has resulted in a wide range of avenues for both sourcing and utilizing hydrogen gas. Moreover, the UK benefits from favourable geological conditions that facilitate large-scale hydrogen storage, with existing storage in salt caverns and ongoing investigations into using disused oil and gas fields beneath the North Sea for storage purposes [128].

2.19.4. Hydrogen strategy, future plan and investment

The UK aspires to be at the forefront of the global hydrogen sector by 2030, demonstrating its leadership with 5GW of low-carbon hydrogen production capacity. This capacity will be critical in driving the country's overall decarbonization initiatives across multiple sectors of the economy. Furthermore, well-defined plans are in place to accelerate progress toward Carbon Budget 6 and, eventually, net zero emissions. This ambitious vision will not only create new job opportunities but also foster clean growth throughout the UK [128]. Considering the British Energy Security Strategy, the government follow 10 GW low carbon hydrogen production capacity enhancement by 2030 cooperating with industries mainly planned to produce by electrolyte [129].

Meeting the UK's 2030 objective will result in significant reductions in emissions. Between 2023 and 2032, it is predicted that using 5GW of production capacity to facilitate the adoption of low-carbon hydrogen will save roughly 41 MMT of CO_2 emissions. This is equivalent to the carbon absorption of 700 million trees throughout the same span [128].

The UK's 5GW aspiration would not only lead to the establishment of a flourishing hydrogen industry but also generate significant economic benefits. By 2030, this initiative could create more than 9,000 job opportunities and contribute £ 900 million (around US$ 1152.2 million) to the Gross Value Added (GVA) of the economy. The UK's ambitious goals also pave the way for a promising future beyond 2030. The assessment indicates that with a strong emphasis on hydrogen, the country could potentially create up to 100,000 jobs and contribute £ 13 billion (around US$ 16.73 million) to the GVA from the hydrogen economy by the year 2050 [128]. In April 2022, the Net Zero Hydrogen Fund (NZHF) was introduced with a value of £ 240 million (around US$ 308.8 million). Its primary purpose is to provide financial assistance for the implementation of hydrogen production initiatives by offering development and capital grants. In England, the Department for Education is allocating an extra £ 3.8 billion (around US$ 4.89 billion) towards skills funding, which is planned to be implemented by the year 2024-25. Hydrogen innovation remains backed by public funders such as the Department for Energy Security and Net Zero, the Department for Business and Trade, and UK Research and Innovation. Their support extends to initiatives like the prominent £ 1 billion (around US$ 1.3 billion) Net Zero Innovation Portfolio. By 2030, a sum of £ 9 billion (around US$ 11.58 billion) will be required to achieve a hydrogen production capacity of up to 10 GW. Forecasts indicate that the UK hydrogen economy's growth will necessitate an investment of £ 2 billion (around US$ 2.57 billion) in hydrogen infrastructure by 2030 [130]. The main principles for the hydrogen strategy pathway are [128]:

- Minimizing the expenses of implementing the plan and continuously reducing costs in the long run, benefiting both UK taxpayers and consumers
- Reducing disruption and expenses for households and consumers
- Maintaining flexibility and adjusting to evolving market conditions
- Promoting economic growth while reducing emissions
- Adopting a comprehensive approach
- Securing advantageous positions for the UK

2.20. United States of America (USA)

2.20.1. Legislation

A program led by the Office of Energy Efficiency and Renewable Energy is working to develop a standard draft to prepare a new standard draft for hydrogen production, utilization, storage, and distribution for national and international application. Different stakeholders are involved in this project such as national laboratory scientists, industrial engineers, standard developers, and organizations under the Department of Energy (DOE) Hydrogen Program's standards [131].

Regarding the hydrogen legislation in the USA, each state has its own policy which may differ widely from state to state. Besides, national regulation would be different from the state's regulations. Recently, DOE released a standard for clean hydrogen generation in September 2022. This standard would consider hydrogen production from a variety of fuels (fossil fuels with carbon capture, utilization, and sequestration (CCUS), fuels that include hydrogen like methanol, and renewable fuels like biomass). Also, they defined clean hydrogen as hydrogen generated with equivalent or less 2 kg CO_2 [132]. In the report it has been mentioned that it is not a regulatory standard, however, it is designated to be a guideline for DOE investment in this technology. The proposed draft is trying to determine the scaling up of the hydrogen generation challenges and proper strategies to tackle the issues. It comprises targeting investment in clean hydrogen production, production cost decrement, market facilitating, and considering regional networks and infrastructure to develop this technology [132]. The factors that DOE should establish in this standard are shown in Fig. 3.

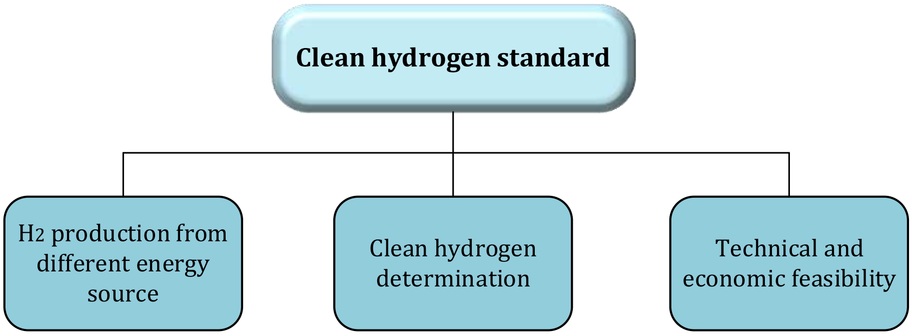

Fig. 3. The DOE establishment in standard preparation

Both downstream and upstream processes and emissions are considered in the lifecycle target of the standard. Downstream processes like defector emissions, electricity production, extraction of any feedstock, and downstream processes such as fuel combustion applied in CO_2 captured compression and defector emission from sequestration and transport. Besides, DOE prepared a national standard draft for hydrogen generation, storage, usage, processing, and delivery as a roadmap and strategy [132]. This roadmap has been designed based on three different parts which are illustrated in Fig. 4.

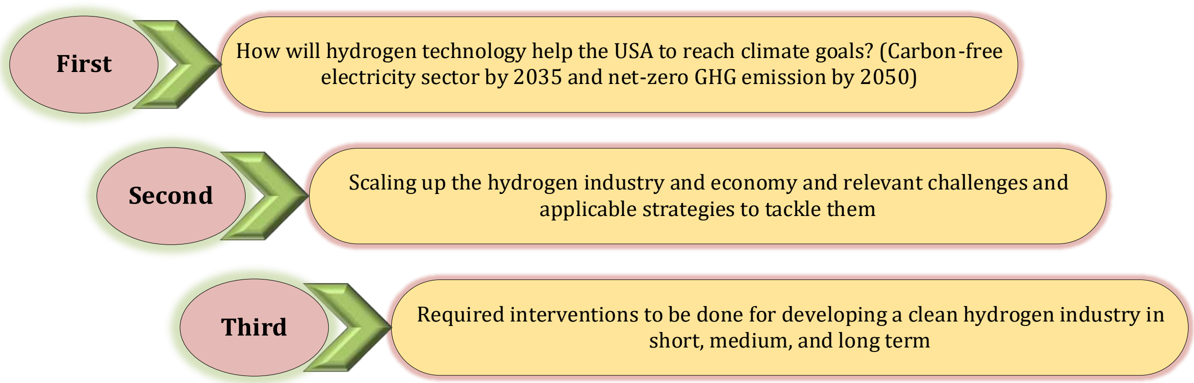

Fig. 4. Three parts of hydrogen technology roadmap defined by DOE

2.20.2. Investment

DOE announced that they have been allocated US$ 750 million to develop the clean hydrogen technology. These resources will be assigned to the U.S. Department of Energy Hydrogen Program which is working under the leadership of the Hydrogen and Fuel Cell Technologies Office (HFTO). It will be spent for different purposes such as safety, manufacturing, standards, development of workforce and education, systems improvement, and research [133]. Shortly, the Biden-Harris Administration intends to unveil the identification of six to ten H2Hubs, which will receive a total combined federal investment of up to US$ 7 billion [134]. The United States has committed US$ 9 billion in financing to encourage the development of clean hydrogen hubs, as well as to advance and extend electrolyzer technology [135]. The Bipartisan Infrastructure Law incorporates US$ 1.5 billion to aid hydrogen electrolysis and US$ 8 billion to finance a comprehensive Regional Clean Hydrogen Hubs program [136].

2.20.3. Hydrogen strategy and future plan

The USA National Clean Hydrogen Strategy investigates how clean hydrogen can support the country's decarbonization objectives in diverse sectors. It offers an overview of current hydrogen-related activities in the USA, along with a strategic blueprint to achieve widespread clean hydrogen production and utilization at significant scales. The document assesses potential scenarios for the years 2030, 2040, and 2050, encompassing hydrogen production, transportation, storage, and application. The DOE Hydrogen Program Plan offers a comprehensive perspective on how to manage and align R&D, and demonstration endeavours within the DOE Hydrogen Program [137]. This strategy is founded on giving priority to three primary approaches, as follows [138]:

1) Focusing on identifying strategic and impactful applications for clean hydrogen
2) Decreasing the expenses associated with clean hydrogen
3) Concentrating on regional networks

The goal of this plan is to ensure the efficient development and broad adoption of clean hydrogen as a powerful tool for decarbonization, maximizing benefits for the United States. These strategies provide targeted opportunities to achieve 10 million metric tons (MMT) of clean hydrogen per year by 2030, 20 MMT annually by 2040, and 50 MMT per year by 2050 [138].

3. Methodology

3.1. Data gathering and limitations

The data collection approach included a comprehensive review of publicly available government reports, policy documents, and international databases on hydrogen standards, legislation, investments, national strategies, and future plans across G20 countries. Key sources were official government websites, energy ministries, and databases like the IEA. To ensure consistency, this study prioritized sources with standardized reporting and cross-referenced data to verify its accuracy.

Several limitations and challenges were encountered during the data collection stage for assessing the maturity of the hydrogen economy in G20 countries. First, data availability and quality regarding hydrogen standards, legislation, and investments vary considerably across countries. Many nations lack comprehensive or up-to-date public information, and inconsistencies in reporting practices limit cross-country comparability. Furthermore, policies and investments in the hydrogen sector are shaped by each country's political context, economic priorities, and energy dependencies, potentially introducing biases in data reporting. For instance, fossil fuel-dependent countries may underreport hydrogen initiatives, while those prioritizing green energy could overstate their progress. National strategies and future plans for hydrogen development are often aspirational and may lack actionable steps or realistic timelines. Additionally, investment data may be biased by undisclosed private sector contributions, and public reports tend to emphasize announced funding over actual expenditures, which can skew perceptions of financial commitment.

A centralized, open-access database for hydrogen economy metrics, regularly updated by international organizations such as the IEA or IRENA, could improve data standardization and accessibility. This platform should include standardized reporting guidelines to ensure consistency across countries. Future research should focus on harmonizing data reporting practices, possibly through international agreements to standardize indicators and improve transparency. Additionally, developing consistent methodologies for reporting private-sector investments would address current data gaps. Longitudinal studies tracking national hydrogen strategy implementation and policy progress would provide insights into their long-term effectiveness. These efforts would enhance the reliability of cross-country comparisons in hydrogen economy assessments.

3.2. Data validation

To ensure the accuracy and reliability of data on hydrogen standards, legislation, investments, national strategies, and future plans within G20 countries, this study implemented a series of validation methods. First, data consistency was confirmed by cross-referencing information from a range of reputable sources, including international databases, government reports, and policy documents, thereby reducing reliance on any single source. Additionally, this study's findings were benchmarked against recent peer-reviewed studies and reports from leading organizations to align with the most current insights. Temporal consistency was ensured by verifying the publication dates of all sources and capturing recent policy and industry developments accurately. This study prioritized sources with standardized reporting practices and rigorous methodologies to mitigate potential biases from less transparent sources. Together, these validation strategies enhanced data reliability, supporting a robust assessment of the maturity of the hydrogen economy across G20 nations.

3.3. Maturity scoring methodology

The Weighted Scoring Model (WSM) method is applied in this study to measure the scoring and assess the maturity of different aspects of the hydrogen economy across G20 countries. The WSM is a decision-making framework designed to assess and rank various options based on multiple criteria. It enables organizations or academics to quantitatively evaluate the strengths of different alternatives by assigning weights to each criterion based on its significance [139]. WSM provides a structured and systematic approach to evaluate multiple options based on various criteria, allowing for a clearer comparison of alternatives. WSM facilitates quantitative analysis, enabling decision-makers to assess options objectively and transparently. This model also promotes stakeholder engagement, as it encourages discussions about the criteria and their weights, fostering a collaborative decision-making environment. Moreover, the flexibility of the WSM allows it to be adapted to different contexts and criteria, making it applicable across various industries and situations.

The initial step involves defining the criteria used for evaluating the options. These criteria should be pertinent to the specific decision and can encompass both qualitative and quantitative measures. In this study, various criteria including legislative and standard frameworks, investments, hydrogen strategies, and future plans have been assessed. Each criterion is assigned a weight that reflects its relative significance in the overall decision-making process, with the sum of all weights ideally equal 1 (or 100%). Subsequently, each option or alternative is assessed against the established criteria and receives a score that indicates its performance. Scores are typically assigned on a standardized scale, where higher scores signify better performance [140]. Each country is assigned a score ranging from 1 to 10, reflecting its level of maturity within each criterion and sub-criterion. A score of 1 indicates the least maturity, while 10 signifies the highest level of maturity achieved. The scoring and classification done in this evaluation is a relative comparison approach. The formula can be expressed as [140]:

$$Weighted\ Score = \sum(Score_i \times Weight_i) \tag{1}$$

Here, i represents each criterion. The assessment of standards and legislation maturity takes into account multiple sub-criteria, that are shown in Fig. 5.

Fig. 5. Sub-criteria of legislation and standard scoring

In evaluating the investment maturity levels among various G20 nations, a comparison has been made concerning the allocation of financial resources toward the development and expansion of hydrogen-related projects and initiatives. This classification is done based on several factors which have been presented in Fig. 6. It has been tried to consider the most reliable and valid reports and documents to assess the financial allocations.

Fig. 6. Sub-criteria of investment scoring

To score the hydrogen strategy and future plan for all twenty countries it has been attempted to consider multiple factors. These sub-criteria which are mainly related to the comprehensiveness of the strategy are presented in Fig. 7. These qualitative elements are the most dominant factors that are analysed in the available documents, national strategies, and government reports. The summary of the scoring approach and relevant definitions are brought in Table 2.

Fig. 7. Sub-criteria of hydrogen strategy and future plan scoring

Table 2. Summary of scoring approach and definition

Score	Legislation	Investment	Strategy & Future plan
10	7 out of 7 factor of Fig. 5	5 out of 5 factor of Fig. 6 with more documented evidence	7 out of 7 factor of Fig. 7
9	6 out of 7 factor of Fig. 5	5 out of 5 factor of Fig. 6	6 out of 7 factor of Fig. 7
8	5 out of 7 factor of Fig. 5 with more documented evidence	4 out of 5 factor of Fig. 6 with more documented evidence	5 out of 7 factor of Fig. 7 with more documented evidence
7	5 out of 7 factor of Fig. 5	4 out of 5 factor of Fig. 6	5 out of 7 factor of Fig. 7
6	4 out of 7 factor of Fig. 5 with more documented evidence	3 out of 5 factor of Fig. 6 with more documented evidence	4 out of 7 factor of Fig. 7 with more documented evidence
5	4 out of 7 factor of Fig. 5	3 out of 5 factor of Fig. 6	4 out of 7 factor of Fig. 7
4	3 out of 7 factor of Fig. 5	2 out of 5 factor of Fig. 6 with more documented evidence	3 out of 7 factor of Fig. 7

3	2 out of 7 factor of Fig. 5	2 out of 5 factor of Fig. 6	2 out of 7 factor of Fig. 7
2	1 out of 7 factor of Fig. 5	1 out of 5 factor of Fig. 6	1 out of 7 factor of Fig. 7
1	0 out of 7 factor of Fig. 5	0 out of 5 factor of Fig. 6	0 out of 7 factor of Fig. 7

Also, the flowchart of methodology and steps applied in this review assessment is presented in Figure 8.

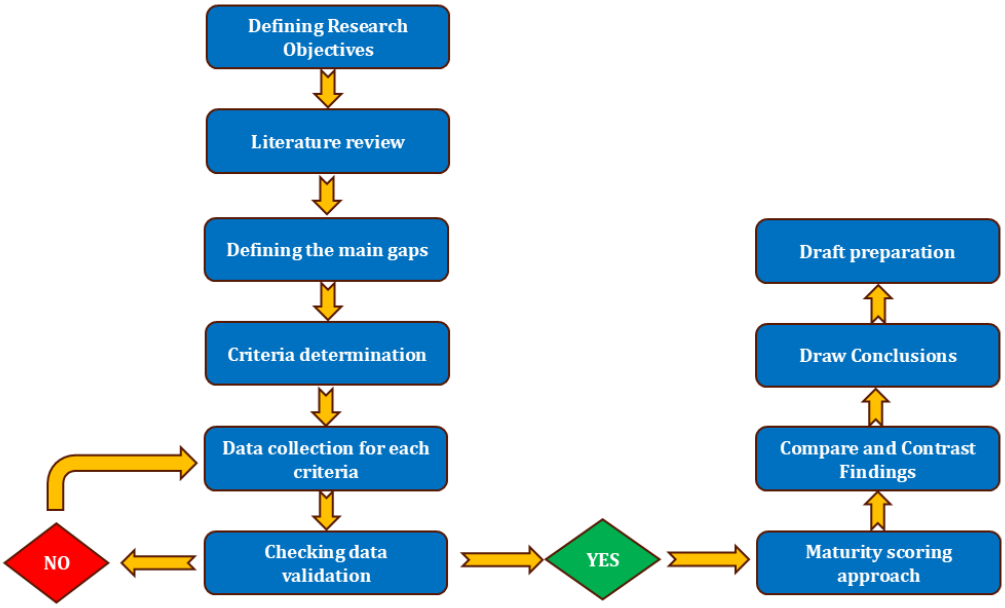

Fig. 8. Flowchart of methodology and steps applied in this review assessment

4. Discussion and comparison

Based on evaluations, among these countries, only China, USA, and UK have an updated hydrogen standard that is released. Some countries have prepared their own national standards in recent years such as Argentina, Italy, France, and so on. Some countries do not have any regulations however have some plans or start some primary actions to develop new legislation for the hydrogen industry such as India. And others do not have any legislation and to the best of conducted review, there are not any clear plans to start a standard development for the hydrogen industry such as Mexico, and Russia. To streamline and standardize the regulatory process, certain governments have adopted the practice of drafting legal documents that are based on widely harmonized standards that already exist [21]. While the main considerable economies, China, the EU, and North America can establish regulations and standards independently for their respective economic regions, it is highly beneficial to harmonize specifications and interfaces of components and subsystems on a global scale. This is particularly important due to the international trade and exchange between these regions, particularly considering the rapid economic growth of Asian and African nations [21].

A well-defined certification process is required to assess the carbon footprint impact at each stage of the entire hydrogen supply chain. When evaluating the effects of carbon management and sustainable development on the supply chain, it's important to consider the economic, societal, and ecological factors involved [141]. This will facilitate and improve the potential for international hydrogen trade. A comprehensive hydrogen certification which comprising all supply chain stages. This will facilitate and improve the potential for international hydrogen trade which could broaden the hydrogen production as well as certifying its derivations and coproducts. Several hydrogen certification approaches have been created in different countries to expand a low-carbon hydrogen technology. However, there are some challenging and differences between the established hydrogen standard that could affect their cross-border applicability, which are displayed in Fig. 9. Established standard should provide an international framework to make a proper connection between hydrogen generation and market demands.

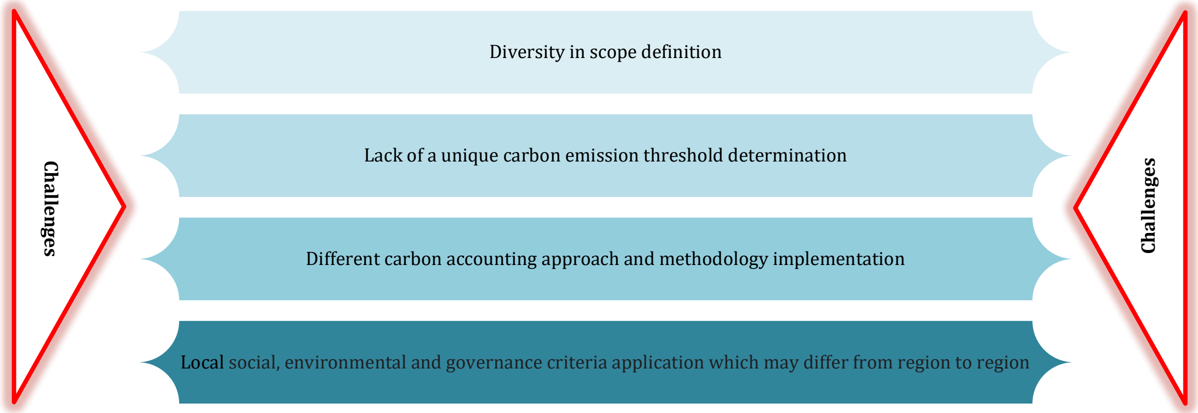

Fig. 9. Main challenges in different established hydrogen standard

These differences result in diverse standard for GH2 label. In other word, same GH2 labelling may indicate different product quality. These barriers have caused the lack of an internationally acceptable standard for hydrogen trade.

To categorize the maturity of countries in terms of investment, the focus is placed on the actual expenditure of funds. Nonetheless, it's important to note that certain reports and references mention the consideration of future financing plans, but these projections or anticipated agreements are not factored into the assessment of investment maturity, as they are primarily based on predictions or expectations. It is important to acknowledge that there might be additional investments reported for all the countries under consideration in unofficial sources or on various websites. However, due to the lack of certainty, these reports were not included in this study. The endeavour has been to evaluate information from the most credible and reliable sources available.

Fig. 10 displays the maturity scoring of hydrogen legislation and investment in G20 countries. The upper-right quadrant represents the nations with the most advanced maturity in both aspects, while the lower-left quadrant showcases countries with less progress in legislation and investment related to hydrogen. Evaluating these results, it becomes evident that the USA and China are the most developed countries in both areas among the G20 members. Following them, the UK and Canada exhibit a high level of maturity, with a slight difference; the UK excels in established legislation, while Canada has directed more financial resources towards hydrogen projects. However, there may be emerging new investment in these countries. At the time of this research, the most reliable and official references were used to consider the investment amounts in these countries. EU have a good position in investment however the legislation should be developed in EU to be compatible with other mentioned nations. Within the G20 countries, India, Indonesia, Russia, Turkey, Saudi Arabia, and Mexico hold the least mature positions in terms of investment and legislation. However, there are some slight differences between the situation of these nations. For instance, India has allocated a larger budget for hydrogen projects in comparison to Turkey and Saudi Arabia. However, India lags behind these countries in terms of legislative and standard establishment progress. Among the G20 nations, Mexico ranks the lowest in both investment and legislation maturity. An average standing is observed among the lower right-hand and upper left-hand quadrant nations, with the key distinction being that the former exhibits a stronger position in investment criteria, while the latter is more advanced in terms of hydrogen standard development. Among these mid-range countries, Italy and South Korea show promise in becoming well-developed in both investment and legislative elements. This potential is due to their higher allocation of funds towards hydrogen-related infrastructure.

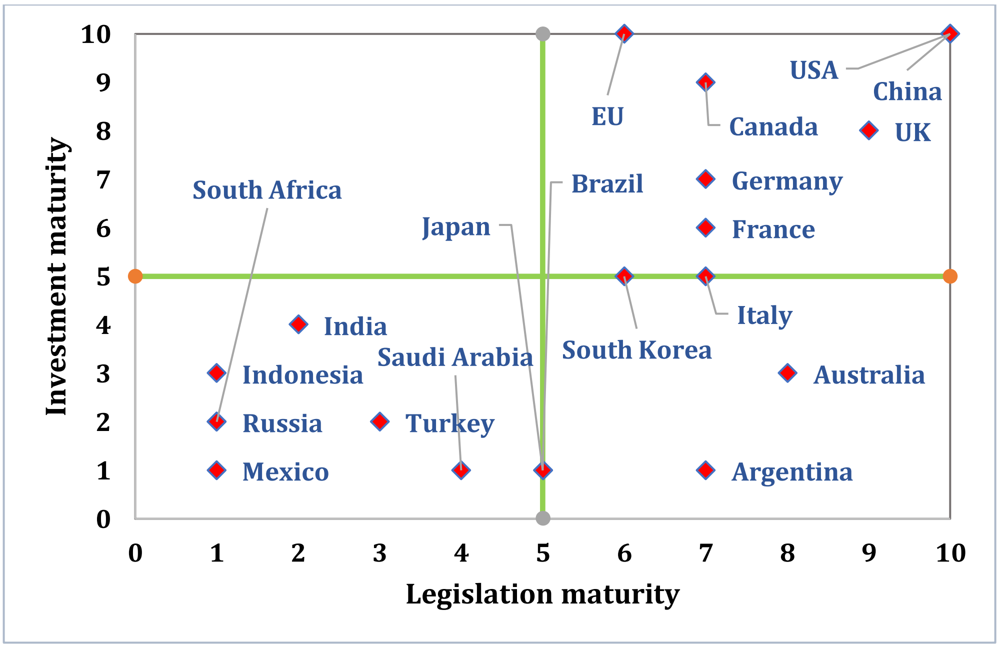

Fig. 10. Hydrogen legislation vs Investment maturities in G20 countries

Fig. 11 depicts a 2x2 matrix illustrating the maturity scoring in legislation as well as strategy and future planning in G20 nations. The underlying principle of this graph is consistent with the previous depiction, where the upper right-hand and lower left-hand quarters indicate the most and least advanced nations, respectively, while the lower right-hand and upper left-hand quarters represent nations falling within intermediate maturity ranges. Evidently, over half of the countries (twelve out of twenty) hold favourable positions in terms of legislation, strategy, and future planning maturity. This observation highlights that most countries have effectively organized their national hydrogen strategies and rely on hydrogen as a pivotal component in achieving their net-zero objectives. The majority of these nations perform well in the criteria related to strategy and future plans. Similar to the patterns seen in legislation and investment maturity, China and the USA occupy the leading positions in these criteria. Furthermore, the UK, Canada, and the EU have formulated comprehensive strategic plans; however, the UK stands out due to its more advanced establishment of a low-carbon hydrogen standard. Conversely, Mexico ranks at the bottom of this assessment.

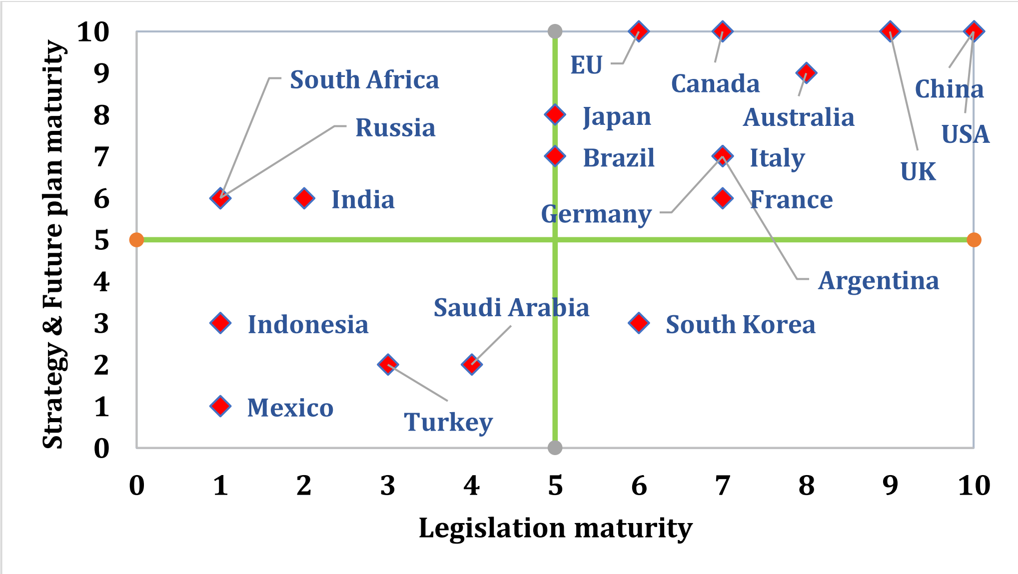

Fig. 11. Hydrogen legislation vs strategy & Future plan maturities in G20 countries

Fig. 12 depicts the strategy & future plan vs. investment maturity scoring in G20 countries. The classification of the maturity rate is the same as in previous plots. The maturity review proves that China, the EU, and the USA are leading in investment and strategy & plan maturities among G20 nations. Subsequently, Canada, the UK, and Germany were assigned the following ranks, respectively. Again, Mexico has ranked as the less matured country in investment and strategy & plan maturities. Among the G20 group, Mexico needs more practical and influential actions to define its net-zero, hydrogen strategy, investment policy, and legislation establishment. The maturity assessments, based on specified criteria, revealed an imbalance in maturity levels for different aspects in some countries. This variation in development may lead to interruptions and challenges in establishing a stable hydrogen economy within these nations. The review indicates that certain countries, such as Japan (strategy and plan score of 8, investment score of 1), display uneven maturity across criteria; similar trends are seen in Brazil, South Africa, Russia, Argentina, and India. Notably, while Argentina and Brazil perform well in legislation and strategic planning, their investment scores of 1 highlight the need for increased financial resources or absorption capacity to prevent disruptions in their plans. In contrast, China, Canada, the EU, the UK, and the USA exhibit stronger alignment across all evaluated criteria, indicating that these nations are advancing all critical aspects of the hydrogen economy in parallel. In addition, these findings indicate that nations with more comprehensive hydrogen legislation also perform better in other criteria, highlighting the essential role of robust regulatory frameworks in advancing the hydrogen economy.

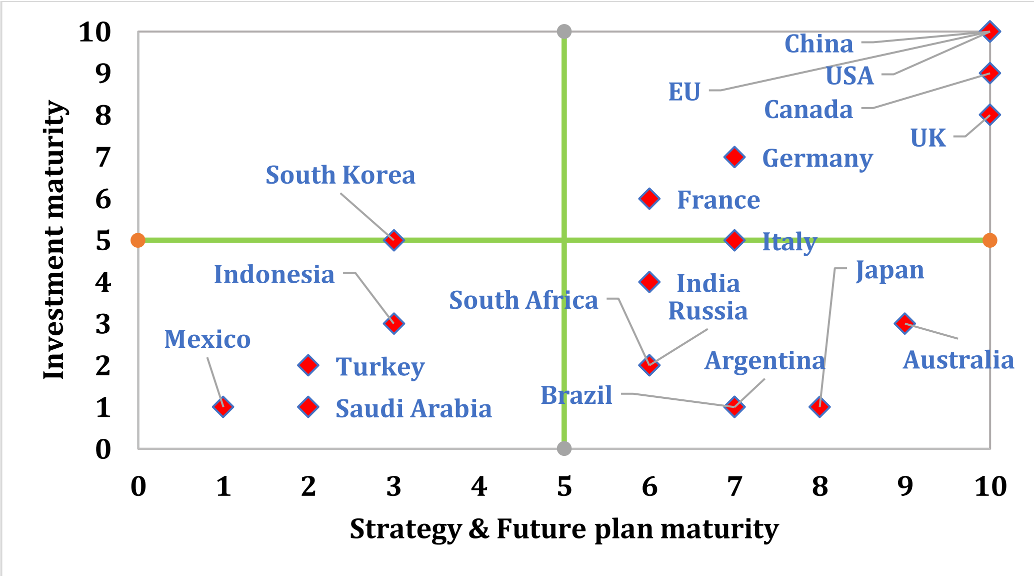

Fig. 12. Hydrogen strategy & Future plan vs investment maturities in G20 countries

The substantial consequences of supply chain disruption encompass environmental, economic, and social aspects, implying that such disruptions lead to incurred expenses [142]. All the factors considered in this study hold significant importance and wield substantial influence over the establishing a widespread hydrogen economy supply chain. The supply chain's robustness relies heavily on each of these elements, and any deficiencies or weaknesses in them could potentially disrupt the entire supply chain. Consequently, it is imperative to create a comprehensive hydrogen standard and strategy that encompasses all stages and components of the supply chain. One potential solution is to combine existing national standards and regulations into a unique international standard that would be internationally accepted among G20 nations. This would facilitate hydrogen trade and advancement. Additionally, enhancing the ability of local laws and circumstances to adapt is of paramount importance in overcoming current obstacles. Prioritizing investment in R&D through collaboration between academia and industry sectors is another crucial aspect that should be emphasized in national agendas. R&D efforts have the potential to mitigate safety concerns and uncertainties associated with hydrogen technology and its application across various sectors. Furthermore, substantial progress is required to reduce the production costs of hydrogen production so that it can compete effectively with other available fuels in the market. The transition of the existing energy system cannot occur unless low-carbon energies like GH2 become economically feasible, which could involve the adoption of cost-competitive technologies and adjustments in energy pricing to account for the external expenses associated with energy production [143]. To foster the development of hydrogen utilization, governments should allocate subsidies to projects related to hydrogen. This financial support would help attract investor interest and provide the necessary backing for the growth of hydrogen-based initiatives. Table 3 presents an overview of all criteria reviewed across all G20 countries.

Table 3. Summary of criteria review for G20 countries

Nations	Legislation/Standard	Investment & Investors	National hydrogen strategy	Future plan & Predictions
Argentina	* Argentina reached a significant milestone in 2006 by enacting its first hydrogen legislation.	* Collaboration between Argentina and Japan to develop GH2 production technology * Approximately US$ 8.4 billion will be invested in GH2 projects by 2028 by government * EU intends to invest approximately US$ 5.7 million in the production and commercialization of GH2	* The Argentine government, in conjunction with private and academic sectors, formulated the 2030 National Low-Emission Hydrogen Strategy in June 2022.	* Generating over 1,000,000 tonnes of GH2 annually by 2030. * Decreasing the carbon footprint of its energy mix by substituting fossil fuels with GH2. * Creating 50,000 job opportunities.
Australia	* Australia adopted national standards and regulations regarding various aspects of hydrogen technology in July 2020. * The Australian government is planning to support the establishment of legislation internationally applicable for hydrogen and other energy certification.	* Allocating more than $ 146 million to hydrogen projects throughout the entire supply chain from 2015 to 2019 by government. * Investing over AUS$ 1.3 billion to develop hydrogen technology by government.	* Examination of the National Hydrogen Strategy to ensure that Australia continues to progress as a prominent global hydrogen leader by 2030	* Creating 10,000 energy apprenticeships over nine years. * Cultivating a greener workforce, in line with the objectives of the National Hydrogen Strategy
Brazil	* No official hydrogen standards in Brazil.	* EU investments around US$ 2.16 billion in GH2 projects	* The Brazilian Hydrogen and Fuel Cell Systems Program, established in 2002 by the MCTI, known ProH2.	* PNH was issued in July 2021 by the MME to promote the growth and establishment of the hydrogen market in Brazil while also facilitating the country's international presence in a financially competitive manner.
Canada	* There are gaps in the current standards that must be addressed to facilitate widespread adoption in Canada. Around 200 experts have been gathered as a group named the Hydrogen Codes and Standards Working Group (CSWG)	* CAD$ 5.6 billion financial allocations in GH2 by government. * Provision of CAD$ 20 billion in financial assistance for Clean Electricity investments in Government Budget for 2023.	* The Hydrogen Strategy for Canada provides a comprehensive roadmap detailing ambitious measures to position hydrogen as a pivotal enabler in achieving Canada's net-zero emissions goal by 2050.	* Emerging as a global leader in the supply of hydrogen technologies * Harnessing the power of hydrogen as a crucial catalyst to achieve the goal of net-zero emissions by 2050 * Opening over 350,000 high-paying job positions at a national level

				* Reaching CAD$ 50 billion by 2050 from export
China	* China has a larger number of national hydrogen standards than the International Electrotechnical Commission (IEC) and the International Organisation for Standardisation (ISO). * In December 2020, China released the "Standard and Evaluation of Low-carbon Hydrogen, Clean Hydrogen, and Renewable Hydrogen".	* Allocating around US$ 10.33 billion is invested annually in hydrogen projects * Other exact amount of public funding is not transparent	* The Chinese government has formulated a comprehensive medium- and long-term development blueprint for hydrogen spanning from 2021 to 2035.	* 50,000 hydrogen fuel cell vehicles on the road and establishing a network of hydrogen refuelling stations by 2025 * Producing from 100,000 to 200,000 tonnes of GH2 per year by 2025 * Reaching 43 million tons of hydrogen production by 2030 * Increasing the share of GH2 in energy mix from 1% in 2019 to 10% by 2030 * Increasing market size by nearly 30 times during this timeframe.
EU	* In October 2021, the European Clean Hydrogen Alliance issued a report identifying the lack of hydrogen standards as a major barrier to the broad adoption of hydrogen technologies and applications. As a result, the alliance created a specialized Working Group focused on hydrogen standardization.	* Investments in electrolyzers could vary from € 24 to € 42 billion by 2030. * Estimating € 220-340 billion of clean electricity implementing renewables and electrolyzers	* In 2020, the EU adopted the hydrogen strategy (COM/2020/301), which introduced targeted policy measures across five key areas.	* A minimum of 6 GW of renewable hydrogen from 2020 to 2024 electrolyzers within the EU * Producing up to 1 million tonnes of renewable hydrogen * From 2025 to 2030, fully integrate hydrogen into the EU's integrated energy system * Installing at least 40 GW of renewable hydrogen electrolyzers by 2030 * Producing up to 10 million tonnes of renewable hydrogen within the EU by 2030
France	* In France, the legal framework governing hydrogen is established in Law-Decree No. 2021-167 dated 17th February 2021. The main purpose of this law is to define and categorize	* € 7.2 billion of public investment towards the development of decarbonized hydrogen by 2030 by government	* As early as 2018, France emerged as one of the pioneering nations to initiate a comprehensive	* Growing the electrolysis technology for industrial decarbonisation

	the various legal classifications of hydrogen. There are no dedicated regulations in place for the transportation, import, and export of hydrogen.	* Allocating an extra € 1.9 billion for the advancement of decarbonized hydrogen technologies by 2030 by government	national hydrogen program. * In September 2020, the Ministry of the Ecological Transition unveiled a national strategy focusing on the advancement of decarbonized and renewable hydrogen in France.	* Expanding the decarbonized hydrogen utilization in the field of heavy-duty transportation * Enhancing the R&D and skill to foster the adoption of future hydrogen applications
Germany	* The majority of the applicable regulations pertaining to hydrogen and fuel cells in Germany presently rely on or need to be adjusted according to European legislation.	* A total of € 7 billion in investments for the development of GH2 by the government * Planning to invest around € 550 million in new hydrogen infrastructure establishment by the government	* The German Federal Government has devised a National Hydrogen Strategy including different aspect of hydrogen	* Diminishing GHG emissions through developing renewable-based hydrogen production * Formulating a regulatory framework that facilitates the development and expansion of the essential transport and distribution infrastructure required for hydrogen * Enhancing the competitiveness of German companies by fostering the adoption, R&D, and hydrogen technologies export * Production 5 GW by the year 2030, with an additional capacity of 5 GW set to be constructed between 2035 and 2040
India	* There is no internationally recognized hydrogen technology standard in India.	* An initial financial expenditure of roughly US$ 2.5 billion * It is estimated that more than € 90 billion will be invested in GH2 by 2030	* The Ministry of Power launched the initial phase of the national GH2 policy on February 17, 2022, with a focus on advancing research, developing infrastructure, and stimulating demand for GH2.	* Investing more in hydrogen development, and establishing * A minimum annual production capacity of 5 million metric tonnes * Positioning India as a prominent global producer and provider of GH2 * Creation of around 600000 jobs by 2030

Indonesia	* There are no laws or standards for hydrogen technology in Indonesia.	* Samsung and Hyundai recently announced their partnership with the Global Green Growth Institute on a project costing US$ 1.2 billion to generate GH2 * The Indonesian government anticipates requiring private sector investments totalling US$ 25.2 billion between 2031 and 2060 to foster the development of GH2	* The Indonesian government predicted that for GH2 development between 2031 and 2060.	* Indonesia has determined that CO_2 emissions diminish through hydrogen technology application for each decade (for instance, 796, 956, and 1526 million tonnes of CO_2 reduction for the 2036-2040, 2041-2050, and 2051-2060 periods).
Italy	* There are some national regulations regarding different aspects of hydrogen technology in Italy. In October 2018, the Ministry of Interior Affairs and the Ministry of Infrastructure and Transport issued updated fire prevention regulations for the design, construction, and operation of hydrogen distribution facilities for vehicles-the only legislation available for hydrogen generation and operations.	* NRRP has earmarked around € 3 billion to enhance hydrogen technology in Italy * European Commission has recently approved an Italian plan worth € 450 million aimed at producing GH2 * Italian Ministry of Economic Development has set a target of investing approximately € 10 billion in GH2 production by 2030	* Italian Ministry of Economic Development in November 2020 published the "Hydrogen Strategy”.	* Considering both short-term and long-term goals, aiming for 2% of national energy consumption to be derived from hydrogen by 2030 and 20% by 2050. * Planning to consider key sectors including chemicals, public transportation, and refining crucial areas for the utilization and advancement of hydrogen * Achieving a reduction of approximately 8 million tons of CO_2 equivalent in emissions by 2030 * Creation of up to 10,000 permanent jobs in the medium term
Japan	* No specific regulations in place regarding the hydrogen in Japan.	* Government planned to invest around US$ 113 billion over the next 15 years in the development of hydrogen technologies	* METI adjusted the first national hydrogen scheme in 2017 named basic strategy, followed by Strategic Roadmap for Hydrogen and Fuel Cell named strategic roadmap which was issued in 2019	* Reducing the hydrogen cost as much as possible competitive with other energy sources * Allocating financial resources for R&D to hydrogen and ammonia usage commercialisation as fuel by 2030 and increasing the number of fuel cell vehicles and

				hydrogen refuelling stations * Hydrogen supply chain improvement
Mexico	* There are no specific regulations regarding hydrogen economy in Mexico.	* It is projected that cumulative investments reaching approximately US$ 8.5 billion by 2050 * GH2 projects in Mexico have planned investments of approximately US$ 1.35 billion	* The Mexican Hydrogen Association has been established to facilitate the improvement of the hydrogen industry in Mexico through effective strategies and actions	* Promoting awareness about the challenges related to hydrogen * Engaging all relevant stakeholders from the public and private sectors who play an effective role in developing the hydrogen industry * Contributing to evaluating the hydrogen landscape in Mexico, including identifying the potential, opportunities, and challenges * Expanding collaboration with national and international organizations on hydrogen projects
Russia	* There is a lack of established standards and legislation specifically addressing hydrogen technology in Russia.	* Russian government plans to invest 9.3 billion Roubles (around US$ 125 million) by the end of 2024.	* The Energy Strategy 2035 was endorsed by the Russian government on June 9, 2020. * An official directive from the Russian government regarding hydrogen policy was issued on April 5, 2021, outlining the country's plans for the development of the hydrogen economy from 2024 to 2050.	* Achieving a 5-9% growth in energy production by 2024, relative to the levels observed in 2018, * Boosting fuels and energy resources exports by 9-15%, * Enhancing investments in the energy sector by 1.35-1.4 times, * Raising Russia's gasification level from 68.6% to 74.7% by 2024 and to 82.9% by 2035.
Saudi Arabia	* Saudi Arabia does not have any special legislation in place to support hydrogen projects.	* US$ 36 billion is planned to invest in hydrogen technology in Saudi Arabia by 2030.	* Reports indicate that Saudi Arabia is currently developing an official strategy for hydrogen.	* Producing 2.9 million tons of clean hydrogen annually by 2030 and 4 million tons by 2035.
South Africa	* No specific standards or legislation for hydrogen technology has been found in South Africa.	* Approximately ZAR 800 million has been allocated by DEA to support the	* The Hydrogen Society Roadmap, released by the Department of	* Developing a market for South African GH2 with the aim of

		transition toward a low-carbon development pathway, including hydrogen * The German development bank, KfW, has launched a program worth € 200 million aimed at providing support for the development of GH2 projects in South Africa.	Science and Innovation in South Africa, establishes a framework for prioritizing the implementation of the hydrogen economy at a national level.	facilitating exports * Heavy-duty transportation decarbonization * Energy-intensive sectors' decarbonization * Promoting the expanded utilization of various forms of hydrogen * Deployment of 10 GW of electrolysis and a minimum annual hydrogen production of 500 kt by 2030, with an increase to 15 GW capacity by 2040. * Generating over 30,000 job opportunities each year by 2040.
South Korea	* No specific standards or legislation for hydrogen technology. Based on the Hydrogen Act scheme, the companies that intend to manufacture fuel cells or hydrogen-related devices must have the local authorities' approval.	* Planning to allocate 34 million US$ on hydrogen promotion by government * In 2019, the HyNet was established with an initial investment of US$ 119 million. * In the year 2021, government allocated approximately US$ 702 million for hydrogen projects * An additional US$ 2.3 billion to develop a hydrogen-powered fuel cell electric vehicle market through public-private partnerships by the end of 2022 * In 2021, five major South Korean conglomerates made a collective announcement about their intentions to invest more than US$ 38 billion in the hydrogen economy by the year 2030.	* Korea presented its Hydrogen Economy Roadmap in January 2019.	* Producing 6.2 million fuel cell electric vehicles and create at least 1,200 refueling stations by 2040. * Planning to put at least 35 hydrogen buses on the road in 2019, with the number progressively increasing to 2,000 by 2022 and 41,000 by 2040. * Increasing the energy sector's fuel cell power generation capacity to 15 GW by 2040.

Turkey	* Turkey has not set any regulations regarding hydrogen technology.	* Investment of nearly US$ 40 billion towards renewable energy initiatives	* Since 2020, the MENR has started developing a hydrogen roadmap including market expansion and applying guidelines for a national hydrogen strategy	* Applying local coal to generate hydrogen * Enhancing the incentive of boron usage for hydrogen storage and conservation * Enhancing the electrolyzer capacity to 5 GW by 2035
UK	* The UK Low Carbon Hydrogen Standard (LCHS) establishes the criteria for determining 'low carbon hydrogen' during the production phase, supporting the implementation of both the UK Hydrogen Strategy and Energy Security Strategy.	* In April 2022, the NZHF was introduced with a value of £ 240 million * In England, the Department for Education is allocating an extra £ 3.8 billion towards skills funding * Allocating £ 1 billion Net Zero Innovation Portfolio * By 2030, a sum of 9 billion pounds will be required to achieve a hydrogen production capacity of up to 10 GW. * Forecasts indicate that the UK hydrogen economy's growth will necessitate an investment of £ 2 billion in hydrogen infrastructure by 2030.	* The UK aspires to be at the forefront of the global hydrogen sector by 2030. * well-defined plans are in place to accelerate progress toward Carbon Budget 6 and, eventually, net zero emissions	* leadership with 5GW of low-carbon hydrogen production capacity * driving the country's overall decarbonization initiatives across multiple sectors of the economy * The government follow 10 GW low carbon hydrogen production capacity enhancement by 2030 cooperating with industries mainly planned to produce by electrolyte * Between 2023 and 2032, it is predicted that using 5GW of production capacity to facilitate the adoption of low-carbon hydrogen will save roughly 41 MMT of CO_2 emissions * Creating more than 9,000 job opportunities and contributing £ 900 million to the GVA of the economy * Creating up to 100,000 jobs and contribute £ 13 billion to the GVA from the hydrogen economy by the year 2050 * Minimizing the expenses of implementing the plan and continuously reducing costs in

				the long run, benefiting both UK taxpayers and consumers * Reducing disruption and expenses for households and consumers * Maintaining flexibility and adjusting to evolving market conditions * Promoting economic growth while reducing emissions * Adopting a comprehensive approach * Securing advantageous positions for the UK
USA	* DOE released a standard for clean hydrogen generation in September 2022. A program led by the Office of Energy Efficiency and Renewable Energy is working to develop a standard draft to prepare a new standard draft for hydrogen production, utilization, storage, and distribution for national and international application.	* DOE announced that they have been allocated US$ 750 million to develop the clean hydrogen technology. * The Biden-Harris Administration intends to unveil the identification of six to ten H2Hubs, which will receive a total combined federal investment of up to $7 billion * $9 billion in financing to encourage the development of clean hydrogen hubs, as well as to advance and extend electrolyzer technology * The Bipartisan Infrastructure Law incorporates US$ 1.5 billion to aid hydrogen electrolysis and US$ 8 billion to finance a comprehensive Regional Clean Hydrogen Hubs program.	* The USA National Clean Hydrogen Strategy investigates how clean hydrogen can support the country's decarbonization objectives in diverse sectors. The document assesses potential scenarios for the years 2030, 2040, and 2050, encompassing hydrogen production, transportation, storage, and application.	* Focusing on identifying strategic and impactful applications for clean hydrogen * Decreasing the expenses associated with clean hydrogen * Concentrating on regional networks * Efficient development and broad adoption of clean hydrogen as a powerful tool for decarbonization * These strategies provide targeted opportunities to achieve 10 million metric tons (MMT) of clean hydrogen per year by 2030, 20 MMT annually by 2040, and 50 MMT per year by 2050.

This maturity scoring approach provides a comprehensive framework to rank and compare the G20 nations based on their progress across critical criteria, enabling stakeholders to assess the maturity of each nation's hydrogen economy development. By evaluating each country's achievements across key areas (legislative support, strategic planning, and financial investments) the scoring system identifies strengths and gaps in existing hydrogen strategies. This ranking enables targeted actions, optimized resource allocation, and encourages collaborative initiatives across nations.

For policymakers, the maturity scores offer insights into specific policy gaps and reveal areas that require enhanced regulatory support or investment. This facilitates the development of policy interventions aligned with international best practices, and the scores also serve as a benchmarking tool, allowing countries to gauge their progress relative to other G20 members. This comparison fosters competitive improvement and encourages the adoption of effective strategies from leading nations. For industry professionals, the rankings highlight market readiness and investment opportunities across various regions, providing crucial data to guide strategic investments in markets where hydrogen infrastructure is maturing rapidly. This insight supports informed decisions regarding market entry, partnerships, and aligning technology with national policy landscapes. For researchers and analysts, this maturity scoring framework offers a standardized methodology to assess the effectiveness of hydrogen development efforts over time. It enables comparisons between countries and helps analyze the specific factors that drive or hinder hydrogen economy growth within each G20 nation.

Through this focused, structured, and comparative approach, the maturity scoring model serves as a powerful tool to support evidence-based decision-making and to promote coordinated progress in developing the hydrogen economy across the G20.

While this study provides a thorough evaluation of hydrogen standards, plans, and investments in G20 countries, certain limitations must be addressed. To begin, the research is based on publicly available national data, which might vary in accuracy, depth, and frequency of updates among countries. This diversity may impact the comparability and accuracy of maturity scores, as some countries may lack consistent reporting, resulting in an underestimation or overestimation of their maturity levels.

Furthermore, because the study focuses on G20 nations, conclusions may not be directly applicable to smaller economies or nascent hydrogen markets, which may face specific difficulties or possibilities not addressed in this analysis. Similarly, the WSM used for maturity ranking provides a formal framework; nevertheless, it includes subjective weighting, which may alter the outcomes depending on the specific emphasis placed on each criterion. While every attempt has been taken to provide an objective assessment and validations performed, future research may benefit from a dynamic model that includes multiple stakeholder perspectives or additional criteria.

Heterogeneity in data quality and availability across the G20 nations may influence investment and policy recommendations based on the results. Researchers and policymakers should keep these limitations in mind when interpreting the study's findings and proceed with caution when applying them to non-G20 contexts.

This study offers a distinctive contribution to the current research landscape by addressing critical gaps in the understanding of hydrogen legislation, standards, and economic maturity among G20 nations. While prior research has generally focused on isolated aspects of hydrogen legislation and its role in decarbonization, few studies have conducted a comprehensive evaluation of hydrogen policies and standards within the context of the leading nations in the hydrogen economy. This work advances existing literature by providing a multidimensional analysis that incorporates both national and international perspectives on hydrogen economy development.

By centering on G20 countries, the study delivers valuable insights into how differing levels of regulatory maturity and financial investment impact the progression of the hydrogen economy. Additionally, this research introduces a novel maturity scoring approach through the application of the WSM, which ranks countries based on their performance across essential criteria, thereby offering a comparative tool for stakeholders. This methodological innovation, previously unexplored in hydrogen economy studies, provides a unique framework for evaluating and guiding the development of hydrogen economies on a global scale. The study's comprehensive analysis - encompassing legislative, strategic, and financial dimensions - fills a substantial gap in the literature and yields practical insights for policymakers, industry leaders, and researchers striving to accelerate the transition to a sustainable hydrogen economy.

5. Conclusion

A comprehensive global standard and policy framework is essential to address the uncertainties and challenges in developing a robust hydrogen economy. An analysis of hydrogen standards and legislation across G20 nations reveals considerable heterogeneity, which may impede widespread trade due to incompatible standards. Establishing internationally accepted standards would facilitate a unified market, starting with a consistent definition of hydrogen and standardized emission thresholds to minimize confusion among stakeholders. Beyond standardization, targeted investment across the hydrogen economy is crucial to enhance legislative effectiveness. Such investments should support the entire supply chain, from workforce education and training to bridge skill gaps to expanded R&D efforts aimed at advancing the technological, environmental, and economic dimensions of hydrogen-related technologies. Additionally, reducing hydrogen production costs is vital to enhance its competitiveness with fossil fuels, particularly in transportation. Efforts should also prioritize the development of efficient logistics networks and the promotion of social awareness around the benefits of hydrogen applications.

Most countries have defined their national hydrogen strategy according to their net zero plan and developing the share of hydrogen in their economy. Some strategies are more detailed, and some others are under development, however, many factors can affect the government's plan. The established strategies in some countries are considered just national development however the defined strategy should include the international connection of the hydrogen market with local industries and policies to tackle the relevant supply chain issues. Unless it can cause a break in the supply chain and consequently the challenges in global trade. One of the main challenges of the hydrogen economy is its scattering as hydrogen is in its early stages of development in many G20 countries.

Maturity assessments showed that the China and USA are the most mature countries in all considered hydrogen economy aspects in this study. Following that, the UK, EU, and Canada were ranked thereafter. Among G20 nations, some countries such as Mexico, Saudi Arabia, Indonesia, and Turkey ranked at the bottom of the list which shows they are far from hydrogen economy maturity from the considered criteria. Some other nations could be placed in the middle range of the ranking list such as South Korea, Russia, and India. However, some countries such as Australia, France, Germany, and Italy are developing hydrogen economy and seems to be competitive with mentioned leaders. However, it should be considered that all G20 countries have significant potential to develop hydrogen portion in their industry. The progress rate would be dependent on two main elements, investment and policy, and regulation determinations. Further study could be done on other aspects of the hydrogen economy in G20 countries. The maturity assessments reveal disparities in hydrogen economy development among the G20 nations, with certain countries exhibiting uneven progress across key criteria. For example, while Japan demonstrates advanced strategy and planning (score of 8), its low investment score (1) indicates a gap in financial commitment, a pattern similarly observed in Brazil, South Africa, Russia, Argentina, and India. Argentina and Brazil, despite robust legislative frameworks, face potential setbacks due to limited investment capacity, which may impede the realization of their hydrogen objectives. In contrast, countries such as China, Canada, the EU, the UK, and the USA show consistent advancement across all evaluated criteria, underscoring the critical role that comprehensive regulatory frameworks play in facilitating balanced progress within the hydrogen economy.

Our findings carry essential implications for global hydrogen development. The study illustrates that cohesive regulatory frameworks are foundational for investment attraction, infrastructure compatibility, and successful international trade, suggesting that coordinated policy efforts could accelerate progress across all G20 nations. The data also reveal that while investment and policy are primary drivers, the effectiveness of financial commitments is limited without aligned standards, as observed in countries with partial maturity across criteria. These insights underscore the importance of a global hydrogen standard that can serve as a foundation for streamlined policymaking, incentivize international collaboration, and enhance global trade opportunities, thereby accelerating the path toward net-zero targets. Moreover, this study identifies several critical challenges: the regulatory fragmentation across G20 nations creates complexities that discourage investment and complicate trade, while gaps in national hydrogen strategies and inconsistent financial allocations hinder the scaling of hydrogen economies. By quantifying these gaps, the maturity scoring framework provides a tool for policymakers to benchmark progress and direct future investments strategically.

The results reveal maturity gaps that can guide engineering design by pinpointing areas where technological development and system integration could be strengthened to align with hydrogen economy targets. These insights support regulatory and policy frameworks, underscoring where targeted regulations and standards could accelerate sector readiness and integration into broader energy systems. From an Environmental, Social, and Governance (ESG) perspective, the methodology emphasizes the importance of sustainability and governance in the hydrogen economy’s development, suggesting pathways for industry and policymakers to balance environmental impact with societal and governance goals. By providing a quantifiable index, the maturity scoring approach offers stakeholders - such as policymakers, engineers, and investors - a structured tool for enhancing the hydrogen economy’s development across critical areas. Our findings contribute to clean energy goals and underscore hydrogen’s potential in achieving climate resilience, supporting both the UN SDGs and the UN Climate Change Framework.

Whilst this study focuses on legislation and standards, investment, national strategies, and future plans for hydrogen in G20 countries, future research could build on this foundational analysis to include environmental impacts, policy implications, and social acceptance of hydrogen technology. Future research may build on this study by examining additional dimensions essential for fostering a resilient hydrogen economy, including technological innovations, workforce development, and sector-specific applications within G20 countries. Longitudinal analyses of policy evolution and its effects on hydrogen economy maturity over time could yield critical insights into progress and barriers, while investigations into regional or subnational policies within larger economies may reveal specific areas primed for accelerated development. Further studies on cooperative mechanisms among G20 nations, particularly in exchanging best practices and harmonizing policies, are recommended to bridge the identified gaps and to lay the groundwork for a cohesive and sustainable global hydrogen economy.

While this study offers a detailed assessment of hydrogen standards, strategies, and investments across G20 nations, some limitations should be noted. The analysis depends on national data that varies in quality and update frequency, which could impact the maturity scores' accuracy. Additionally, insights from this G20-focused study may not apply directly to smaller economies or emerging hydrogen markets, which face distinct challenges. The WSM used here, while systematic, involves subjective weighting, which may influence results based on the importance assigned to each criterion. These limitations suggest that findings may not fully capture the progress of nations with rapid but less formalized hydrogen development. Data variability also means that investment and policy recommendations should be interpreted cautiously, particularly outside the G20. Future research could enhance these conclusions by standardizing hydrogen economy metrics globally and refining maturity models to include more specific indicators, like regional investment data or technology-specific progress. This would address data limitations and provide greater insight into how policy alignment and standards drive the hydrogen transition.

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