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HYDROGEN DEVELOPMENT: LEGAL CHALLENGES AND CURRENT TRENDS

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Hydrogen is emerging as a crucial element in the global transition to sustainable energy, offering a viable alternative to fossil fuels. Its potential to decarbonize hard-to-abate sectors such as heavy industry, transportation, and power generation has driven significant investment and policy development worldwide. However, hydrogen's widespread adoption faces legal, regulatory, and economic challenges. This article explores these issues, focusing on production methods, certification schemes, safety regulations, intellectual property disputes, and infrastructure development. A major concern is the classification of hydrogen based on production methods, from carbon-intensive gray and brown hydrogen to low-carbon blue and renewable-based green hydrogen. While green hydrogen is the most sustainable, its high costs and infrastructure requirements hinder large-scale deployment. Regulatory inconsistencies, market fragmentation, and safety concerns further complicate hydrogen's growth. The study examines global legal frameworks, highlighting national and regional strategies, including the European Union's hydrogen policies, the United States' Hydrogen Earthshot initiative, and hydrogen governance in China, Japan, and emerging economies. It also assesses international cooperation efforts, such as standardizing certification schemes and cross-border hydrogen trade. Technological advancements, including improved electrolysis efficiency, fuel cells, and large-scale hydrogen storage, are evaluated for their role in reducing costs and enhancing feasibility. Finally, this article provides a comprehensive analysis of the evolving hydrogen landscape, emphasizing the legal and policy mechanisms needed to facilitate a just, efficient, and sustainable hydrogen economy that contributes to achieving global net-zero targets.

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1. INTRODUCTION

Following several years of research by experts and scientists on the effects of climate change and the increasing prominence of global warming and ozone layer depletion as a global concern, in 1988, the United Nations (UN) established the Intergovernmental Panel on Climate Change (IPCC). This body has responsibility for assessing climate change, and it has identified anthropogenic climate change as an urgent issue.[1] The assessment reports published thereafter by the IPCC played a key role in raising global concern and inspiring action against climate change.[2] This resulted in the creation and implementation of a major international treaty in 1992, the United Nations Framework Convention on Climate Change (UNFCCC). This was followed by the Kyoto Protocol in 1997, and the Paris Agreement in 2015.[3] The UNFCCC is the most important international instrument to emerge thus far on climate change, and it was complimented and reinforced by the First Compliance Period of the Kyoto Protocol (2008-2012),[4] with the Paris Agreement since having been ratified in order to further support its goals. A range of additional complimentary initiatives and actions have been undertaken as part of the global commitment to fight climate change, including the incorporation of Climate Action as one of the United Nations Sustainable Development Goals (SDGs).[5]

Understanding the cause of climate change was crucial in efforts to mitigate its effects. Research has found that about 75% of global greenhouse gas emissions and nearly 90% of carbon dioxide emissions are

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[1] United Nations, 'From Stockholm to Kyoto: A Brief History of Climate Change' (UN Chronicle, June 2007) https://www.un.org/en/chronicle/article/stockholm-kyoto-brief-history-climate-change accessed 31 October 2023.
[2] IPCC, 'History of IPCC' https://www.ipcc.ch/about/history/ accessed 30 October 2023.
[3] Thomas L Muinzer, *National Climate Change Acts*, ch 1 (Hart 2020) 23–39.
[4] United Nations (n 1).
[5] Eduardo G Pereira, Thomas L Muinzer and Patrick R Baker, *Energy Law and the Sustainable Development Goals* (Routledge 2024).

attributable to the use of fossil fuels such as coal, oil, and gas by humans, making it the largest contributor to global climate change.[6] The IPCC indicates that to avert the worst impacts of climate change, the global temperature increase needs to be limited to 1.5°C above pre-industrial levels.[7] To reach carbon neutrality and limit the earth's temperature to the 1.5°C threshold as adopted in the Paris Agreement, these emissions must be reduced by 45% by 2030 and reach net zero by 2050.[8] This makes the modern energy transition a challenging one as, unlike the past energy transitions which were gradual, this transition necessitates a rapid paradigm shift and complete transformation of our energy production and consumption patterns.

Since the ratification of the Paris Agreement, commendable efforts have been made to decarbonize energy systems. Since 2020, investment in clean technology has been increasing by around 12% per year, wind and solar power generation has been growing by 15-20% per year, and there is strong momentum in clean technologies like low-emission hydrogen, new battery technology, and carbon capture and storage (CCS) among others.[9] Notably, green hydrogen has been gaining momentum as a particularly viable green alternative, and some consider it to be an essential missing piece of our clean energy puzzle.[10] Low-carbon hydrogen could make a crucial contribution to the decarbonization of industries whose emissions are difficult to abate, like steel, chemicals, aviation, shipping, and long-

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[6] United Nations, 'Causes and Effects of Climate Change' (Climate Action) https://www.un.org/en/climatechange/science/causes-effects-climate-change accessed 1 November 2023.

[7] IPCC, 'Special Report: Global Warming of 1.5°C' (*Intergovernmental Panel on Climate Change*) https://www.ipcc.ch/sr15/ accessed 8 March 2025.

[8] United Nations, 'Net Zero Coalition' (Climate Action) https://www.un.org/en/climatechange/net-zero-coalition accessed 29 October 2023.

[9] Fatih Birol, 'A Call to Clean Energy' (*International Monetary Fund*, December 2022) https://www.imf.org/en/Publications/fandd/issues/2022/12/a-call-to-clean-energy-fatih-birol accessed 29 October 2023.

[10] Hydrogen Council, 'Why Hydrogen?' https://hydrogencouncil.com/en/why-hydrogen/ accessed 29 October 2023.

haul road transportation.[11] It has been estimated that green hydrogen could contribute to reducing annual global emissions by more than 20% by 2050.[12] For instance, the steel industry accounts for 8% of annual global emissions and by adopting green hydrogen technology, it is estimated to contribute to nearly 20% of emissions reduction.[13]

Hydrogen is an abundant element, has a high energy content per unit of weight,[14] and can be produced from a wide range of sources such as water, biomass, fossil fuels, and renewables (e.g., wind and solar).[15] Hydrogen has a diversity of potential supply sources, which is an important reason why it is becoming such a promising energy carrier.[16] It has been estimated that if deployed at scale, hydrogen can reduce annual carbon emissions by roughly 6 gigatons compared to today's levels.[17] While there are prospects for hydrogen energy, it is notable that the environmental impact and energy efficiency of hydrogen depends on how it is produced.[18]

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[11] Wilhelm Schmundt and others, 'Building the Green Hydrogen Economy' (*BCG*, 21 March 2023) https://www.bcg.com/publications/2023/strategies-to-build-green-hydrogen-economy accessed 30 October 2023.

[12] Bernd Heid, Alma Sator, Maurits Waardenburg and Markus Wilthaner, 'Five Charts on Hydrogen's Role in a Net Zero Future' (McKinsey Sustainability, 25 October 2022) https://www.mckinsey.com/capabilities/sustainability/our-insights/five-charts-on-hydrogens-role-in-a-net-zero-future accessed 28 October 2023.

[13] McKinsey & Company, 'What Is Hydrogen Energy?' (27 September 2023) https://www.mckinsey.com/featured-insights/mckinsey-explainers/what-is-hydrogen-energy accessed 29 October 2023.

[14] Energy Information Administration, 'Hydrogen Explained' https://www.eia.gov/energyexplained/hydrogen/ accessed 27 October 2023.

[15] Office of Energy Efficiency & Renewable Energy, 'Hydrogen Fuel Basics' (Hydrogen and Fuel Cell Technologies Office) https://www.energy.gov/eere/fuelcells/hydrogen-fuel-basics accessed 27 October 2023.

[16] Fuel Cell Technologies Office, *Hydrogen Production* (US Department of Energy 2016) 1.

[17] Hyundai, 'Hydrogen Could Contribute to 20% of CO_2 Emissions Reduction Targets' (November 2017) https://www.hyundai.news/eu/articles/press-releases/hydrogen-could-contribute-to-20-of-co2-emissions-reduction-targets-by-2050.html accessed 1 November 2023.

[18] US Department of Energy, 'Hydrogen Production and Distribution' https://afdc.energy.gov/fuels/hydrogen_production.html accessed 28 October 2023.

Commonly, hydrogen is categorised as brown, black, white, gray, blue or green hydrogen based on how it is produced.[19]

There are several routes to hydrogen production, the most common today being the thermal processes.[20] Thermal processes involve the steam reformation of hydrocarbon fuels such as natural gas, diesel, coal, biomass, or gasification, which emits carbon dioxide and high greenhouse gases while producing brown, black, or gray hydrogen, accounting for approximately 95% of all hydrogen produced today.[21] 'Blue' hydrogen is increasingly being promoted, which also stems from fossil fuel sources but employs carbon capture and storage (CCS), making it greener than most other hydrogen categories.[22] However, research suggests that blue hydrogen can have negative climatic consequences as not all carbon emissions can be captured and stored, and emissions of methane arising from blue hydrogen processes are 100 times more powerful and harmful than carbon dioxide emissions.[23] Thus, as we move forward to a greener future, green hydrogen is being considered instead, involving the climate-friendly process of electrolysis. Electrolysis is a carbon-free process which uses renewable resources like water, producing the cleanest form of hydrogen (i.e., 'green' hydrogen).[24] The process of electrolysis utilizes electric current to split water into its constituent elements, hydrogen and oxygen. When the electricity employed in this process is generated from renewable energy sources such as wind, solar, geothermal, and

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[19] World Economic Forum, 'Grey, Blue, Green – Why Are There So Many Colours of Hydrogen?' (27 July 2021) https://www.weforum.org/agenda/2021/07/clean-energy-green-hydrogen/ accessed 28 October 2023; EG Pereira, OJ Olujobi, A Fossa and TL Muinzer, 'A Road to Energy Transition with Hydrogen and Carbon Capture and Utilization (CCU) Products Labelling' (2024) 22(3) Oil, Gas & Energy Law.

[20] Office of Energy Efficiency & Renewable Energy (n 13).

[21] ibid.

[22] Robert W Howarth and Mark Z Jacobson, 'How Green Is Blue Hydrogen?' (12 August 2021) 9 Environmental Science & Engineering 1673.

[23] ibid.

[24] Office of Energy Efficiency & Renewable Energy, 'Hydrogen Production: Electrolysis' https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis accessed 28 October 2023.

hydroelectric power, or from nuclear energy, the production phase does not result in significant greenhouse gas emissions.[25] This process allows energy derived from renewable sources to be stored on a large scale, which is a significant benefit in its own right given that existing renewable energy storage technologies are currently insufficient, including battery storage. Green hydrogen therefore has the potential to significantly contribute to the attainment of carbon neutrality and to mitigate the adverse effects associated with climate change.

While hydrogen is a prevalent gas, estimated to constitute approximately 90% of the total mass of the universe, its production can be complex, as it is typically necessary to extract hydrogen from other substances, most commonly hydrocarbons.[26] The path to carbon neutrality via clean hydrogen currently seems to be a challenging one. The greatest challenge for green hydrogen in particular appears to be posed by a need to produce it at a lower cost, so that it can become cost competitive with conventional fuel sources.[27] Moreover, because hydrogen contains less energy per unit volume than other fuel sources, its transportation, storage, and distribution is expensive, and building infrastructure for its distribution requires high initial capital (and its properties also pose unique challenges, including flammability).[28] If we are to reach the goal of climate neutrality by 2050, conducive policies to scale up investments and reduce costs must be adopted alongside initiatives to facilitate operation of existing industries by carbon capture, utilization and storage (CCUS) in sectors that are hard to abate.

The objective of this article is to delve into the increasing prominence of hydrogen as an alternative to fossil fuel energy and the different paths to

[25] Fuel Cell Technologies Office (n 14).
[26] TrendsFormative, 'Hydrogen: Challenges & Opportunities' (15 February 2021) https://trendsformative.com/hydrogen-challenges-and-opportunities/ accessed 29 October 2023.
[27] Fuel Cell Technologies Office (n 14).
[28] U.S. Department of Energy (n 16).

hydrogen production, and to assess the legal and policy implications and overall prospects and challenges associated with each path. This study will explore how different countries are advancing cleaner hydrogen production and building a hydrogen-based energy ecosystem. It will look at policies and initiatives shaping this transition, such as the European Union's hydrogen strategy, China's push to make hydrogen one of its six key industries for the future, and Japan's national hydrogen plans. It will also examine India and South Korea's legal measures to support hydrogen energy, the United States' investments in clean hydrogen—including its Hydrogen Earthshot program to drive down costs—and efforts by Japan, Qatar, and the Netherlands to improve hydrogen production and supply chains using existing infrastructure. Finally, the study will consider how emerging economies are approaching hydrogen development.[29] The article thus seeks to offer value in understanding hydrogen energy as an alternative to fossil fuels by analyzing the prospects and challenges associated with different hydrogen paths, and studying the best practices and trends adopted by the future leaders of hydrogen energy in an attempt to offer insights and solutions as we look forward to a green future, which seems to be incomplete without hydrogen energy development.

2. BACKGROUND TO HYDROGEN

By definition, hydrogen is simply a colourless gas. Experts consider that hydrogen has an essential and expanding role to play in the future of societal decarbonisation.[30] This means hydrogen itself has a very particular range of merits in the context of energy governance pertaining to clean energy production and emissions reduction.[31] These merits are well summarised in the UK policy report, '*The Role of Hydrogen in Delivering*

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[29] World Economic Forum, 'Which Countries Could Become the World's Hydrogen Superpowers?' (14 February 2022) https://www.weforum.org/agenda/2022/02/these-countries-could-become-world-leaders-in-clean-hydrogen/ accessed 1 November 2023.
[30] Marco Alverà, *The Hydrogen Revolution: A Blueprint for the Future of Clean Energy* (Hodder & Stoughton 2021).
[31] IRENA, *Hydrogen: A Renewable Energy Perspective* (International Renewable Energy Agency 2019).

Net Zero'.[32] The report underlined some benefits of hydrogen as an extremely abundant element, which can be produced from any primary energy source, such as fossil fuels and renewables.[33] Many process technologies ranging from chemical, biological, electrolytic, photolytic, and thermo-chemical can be employed. Every technology offers distinct opportunities, advantages, and challenges, and is at a different level of development. A number of factors, including feedstock availability locally, technological maturity, market demand and applications, policy concerns, and cost, will affect the selection and timeliness of the many hydrogen production choices.[34]

Moreover, it has been posited that hydrogen has zero carbon emissions during its use and the highest energy density values by mass of any fuel between 120 and 142 MJ/kg.[35] The flexibility level of hydrogen has also been recognised, given that it can be used across a wide range of energy system applications, including heating, power, industry, and transport. Thus, it can be burnt or utilised for power and heat generation in a fuel cell. A further benefit of hydrogen is that it is used for industrial feedstock and can be stored efficiently in varying scales and forms for long durations, with the possibility to be converted to other carriers, such as ammonia and Liquid Organic Hydrogen Carriers (LOHC).[36] In addition, hydrogen can be transported through pipelines as either compressed or liquefied gas, e.g., as LNG. This facilitates long-distance transportation. With the right safety management and protocols, the risks of hydrogen can be effectively controlled. While hydrogen is naturally more volatile and flammable than natural gas, recent advances in storage technology, handling procedures, and safety regulations have significantly reduced associated risks, making

[32] Hydrogen Taskforce, *The Role of Hydrogen in Delivering Net Zero* (UK 2020).
[33] *Ibid*, p.10.
[34] IEA, *Hydrogen Production and Storage* (International Energy Agency) https://iea.blob.core.windows.net/assets/e19e0c2a-0cef-4de6-a559-59d0342974c3/hydrogen.pdf accessed 12 April 2025.
[35] *Ibid*.
[36] *Ibid*.

hydrogen use in controlled environments safer than in previous applications or unregulated settings.[37] Overall, as an abundant element, hydrogen is extremely versatile and has a promising potential to play an expanded role in energy systems.

As technology continues to advance, the future of hydrogen production looks promising for both the environment and the economy. It is important to remember that large-scale hydrogen production is unlikely to occur anytime soon. The foregoing discussion has identified and highlighted the critical contribution that green hydrogen and blue hydrogen are well placed to make in particular in the context of the energy transition in going forward.

3. THE IMPORTANCE OF A POLICY AND REGULATORY FRAMEWORK FOR HYDROGEN AND LEGAL CHALLENGES IN HYDROGEN DEVELOPMENT

Today, hydrogen is increasingly recognized as a vital component in the global transition to clean energy. The development of hydrogen, however, faces a complex web of legal challenges that must be addressed to unlock its full potential. The first challenge particularly in developing jurisdictions is the lack of fit for purpose policy and regulatory frameworks for the production, transportation and use of hydrogen. In Namibia for example, the absence of a coherent and standardized legal and regulatory framework for hydrogen undermines the potential advantages that such production could offer to Namibia, a developing nation striving to promote trade and investment with the aim of achieving sustainable development. The primary objectives of developing a policy and regulatory framework for green hydrogen include:

[37] *Ibid*.

i. Facilitating Investment: Attracting private sector investment by providing clear guidelines and incentives.

ii. Ensuring Safety: Establishing safety standards for production, storage, transport, and use of green hydrogen.

iii. Promoting Research and Innovation: Encouraging R&D initiatives that can lead to technological advancements in green hydrogen production and applications.

iv. Supporting Infrastructure Development: Identifying necessary infrastructure requirements for effective distribution networks.

v. Encouraging International Collaboration: Fostering partnerships with other nations to share best practices and technologies.

A second challenge pertains to various hydrogen regulations, which often lack clarity and consistency. These regulations vary by jurisdiction . The lack of a unified regulatory framework creates uncertainty and obstacles for industry players,[38] and it is also a major obstacle to the growth of the industry. As clarified, for example, by the industry experience in the United Kingdom and the European Union, the hydrogen sector needs clear and consistent regulations to provide the level of certainty required for long-term investment.[39]

Many governments have complex regulatory difficulties in respect to hydrogen. In the European Union, the regulatory environment is complicated, with numerous, intricate directives and laws covering manufacture, transit, and usage. Belgium, for example, has passed

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[38] US Department of Transportation, *Hydrogen Fuel, Definitions and Requirements* (2020).
[39] Michael Liebreich, 'Separating Hype from Hydrogen' (BloombergNEF, 8 October 2020) https://about.bnef.com/blog/liebreich-separating-hype-from-hydrogen-part-one-the-supply-side/?fbclid=IwAR3HOZPYmKyDoF2vEAxNcMJwEft-yB43DNM32Vl3WtxH0qWUvlvLzafaOw4 accessed 12 April 2025.

legislation controlling green hydrogen transit but not production, highlighting the challenges created by the complexity of EU-wide hydrogen rules.[40] For instance, Belgium has legislation regulating the transportation of green hydrogen but has yet to establish laws for its production due to these complexities.[41] The EU's Hydrogen Strategy aims to address these tensions and create a cohesive framework for hydrogen development.[42] The development of hydrogen technologies relies heavily on intellectual property (IP) protection. However, IP disputes and patent infringement claims are common in the industry.[43] A lack of standardisation across hydrogen technologies exacerbates IP issues, making collaboration and innovation more difficult. Many companies like Air Liquide and Hydrogenics have been involved in high profile patent disputes, highlighting a need for clearer IP guidelines. The European Patent Office has established a specific section for hydrogen-related patent applications, acknowledging the industry's growth.

Furthermore, hydrogen development raises safety and liability concerns. Safety concerns are related to the higher flammability, ignition, leakage and diffusion risks of hydrogen than more common substances in the energy system such as natural gas. Hydrogen's flammability characteristics present higher risks than natural gas. Hydrogen is highly flammable and ignites at much lower concentrations in the air than natural gas. It also has a lower ignition energy threshold, making it more susceptible to ignition from minimal sparks or heat sources. Unlike natural gas, hydrogen flames are nearly invisible, making it difficult to detect and increasing safety risks

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[40] European Commission, *A Hydrogen Strategy for a Climate-Neutral Europe* (2020) https://energy.ec.europa.eu/system/files/2020-07/hydrogen_strategy_0.pdf accessed 20 July 2024.

[41] R Fleming (ed), 'Current Hydrogen Regulation on the Continents', in *The Cambridge Handbook of Hydrogen and the Law* (Cambridge University Press 2024) 11–112.

[42] Steve Barrett, 'The European Hydrogen and Fuel Cell Strategic Research Agenda and Deployment Strategy' (2005) 2005(5) Fuel Cells Bulletin 12–19;
European Commission, *Hydrogen and Fuel Cell Technologies* (2022).

[43] Bloomberg Law, 'Hydrogen Technology Patent Disputes on the Rise' (2022).

in instances of fire.[44] In addition, hydrogen can rapidly evaporate and mix with air, which in the event of ignition may lead to explosions. [45]

Due to its low molecular weight, hydrogen poses significant leakage risks, as it is both lighter and more permeable than natural gas. Indeed, hydrogen is the lightest of all gases, and is fourteen times less dense than air.[46] The small size of hydrogen molecules can allow it to escape through materials such as metals and plastics, with the risk of accidental hydrogen release. This property makes it challenging to contain hydrogen within conventional natural gas infrastructure, which is designed for a heavier substance. Hydrogen's ability to leak into the atmosphere more quickly also increases the likelihood of hazardous accumulation in enclosed spaces, which could lead to combustion or explosions if not detected and managed effectively.[47] Due to these particular properties, it is paramount to carefully select the materials for the infrastructure where hydrogen will be produced, transported, stored and used. Such facilities must be designed and built to prevent, identify and mitigate hydrogen release and to properly contain it.

The adoption and implementation of safety measures to prevent accidents and mitigate potential hazards from hydrogen projects is a key component of any effective regulatory framework for hydrogen developments. Operational safety in hydrogen projects is governed by a combination of international standards and national regulations designed to ensure the safe production, storage, transportation, and utilization of hydrogen. Key frameworks include international standards by the International Organization for Standardization (ISO), namely ISO 14687 (2019), which specifies quality requirements for hydrogen fuel; ISO/TR 15916 (2015)

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[44] International Energy Agency, *Global Hydrogen Review 2024: Hydrogen Production* (IEA 2024) 4 https://www.iea.org/reports/global-hydrogen-review-2024/hydrogen-production
[45] M Calabrese et al, 'Hydrogen Safety Challenges: A Comprehensive Review on Production, Storage, Transport, Utilization, and CFD-Based Consequence and Risk Assessment' (2024) 17 *Energies* 1350 https://doi.org/10.3390/en17061350
[46] Ibid.
[47] Ibid..

covering basic safety considerations for hydrogen systems, and ISO 19880-1 (2020) on safety in hydrogen fueling stations.[48] Similarly, since 2011 in the United States, the National Fire Protection Association (NFPA) has adopted and updated the NFPA 2, Hydrogen Technologies Code which provides detailed safety requirements for hydrogen technologies.[49]

Several governments have adopted regulations on operational safety for hydrogen projects. In the United States, OSHA Standard 1910.103 was updated in 2011 to cover safety protocols for hydrogen systems, including storage and piping.[50] In the European Union the *Atmosphères Explosibles* (ATEX) Directives cover hydrogen projects.[51] The ATEX 94/9/EC (1994) addresses equipment used in explosive atmospheres, including hydrogen, while ATEX 99/92/EC (1999) addresses safety in potentially explosive work environments.[52] The Pressure Equipment Directive (2014/68/EU) sets rules for the design and manufacture of pressure equipment, relevant to hydrogen storage.[53] In turn, Japan's High Pressure Gas Safety Act (1951), with ongoing updates, regulates the production and storage of high-pressure gases, including hydrogen.[54] The United Kingdom has had a diverse regime governing hydrogen that was partially updated and

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[48] ISO 14687 (2019), ISO/TR 15916 (2015), ISO 19880-1 (2020).

[49] National Fire Protection Association, *NFPA 2, Hydrogen Technologies Code* (NFPA 2023).

[50] Occupational Safety and Health Administration, *Hydrogen Systems* (OSHA Standard 1910.103, updated 2011) https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.103 accessed 21 February 2025.

[51] Directive 94/9/EC of the European Parliament and of the Council of 23 March 1994 on the approximation of the laws of the Member States concerning equipment and protective systems intended for use in potentially explosive atmospheres [1994] OJ L100/1 (ATEX 94/9/EC).

[52] Directive 99/92/EC of the European Parliament and of the Council of 16 December 1999 on minimum requirements for improving the safety and health protection of workers potentially at risk from explosive atmospheres [1999] OJ L23/57 (ATEX 99/92/EC).

[53] Directive 2014/68/EU of the European Parliament and of the Council of 15 May 2014 on the harmonisation of the laws of the Member States relating to the making available on the market of pressure equipment [2014] OJ L189/164 (Pressure Equipment Directive).

[54] High Pressure Gas Safety Act (1951) (Japan), as amended.

consolidated under the Energy Act 2023, which includes a focus on operational and practical safety issues.[55]

These standards and regulations adopt safe practices across the hydrogen industry, addressing hydrogen's unique properties and potential hazards.

There are several databases that gather information on accidents related to hydrogen projects. These databases include the Hydrogen Incident and Accident Database (HIAD), developed by the European Commission's Joint Research Centre[56]; the Hydrogen Tools (H2Tools) Incident Database administered by the Pacific Northwest National Laboratory[57], and the European Hydrogen Safety Panel (EHSP) Reports.[58]

Accidents during production, transportation, or storage can have severe consequences. The allocation of liability and insurance coverage for hydrogen-related risks is still unclear, hindering investment in the sector. In the United States, the Compressed Gas Association provides guidelines for hydrogen safety,[59] while the European Union's Hydrogen Strategy emphasises the need for standardized safety protocols.[60]

A key topic to address is how to ensure that the hydrogen produced comes from renewable energy sources. For this purpose, several countries have established certificate of origin schemes. The European Union (EU) CertifHy project has developed a certification system for green and low-carbon hydrogen, providing Guarantees of Origin (GOs) to verify the

[55]Energy Act 2023 (UK), ss 56–142.
[56] European Commission Joint Research Centre, *Hydrogen Incident and Accident Database (HIAD)* https://data.jrc.ec.europa.eu/collection/id-00295 accessed 18 February 2025.
[57] Pacific Northwest National Laboratory, *Hydrogen Tools (H2Tools) Incident Database* https://h2tools.org/lessons accessed 18 February 2025.
[58] European Hydrogen Safety Panel (EHSP), *Reference Documents* https://www.clean-hydrogen.europa.eu/get-involved/european-hydrogen-safety-panel-0/reference-documents_en accessed 18 February 2025.
[59] Compressed Gas Association (CGA), *CGA G-5: Hydrogen* (9th edn, 2024).
[60] European Commission, *A Hydrogen Strategy for a Climate-Neutral Europe* (COM(2020) 301 final).

renewable nature of hydrogen.[61] Furthermore, the Renewable Energy Directive II (RED II) sets criteria for renewable hydrogen, including greenhouse gas emission savings and sustainability requirements.[62]

In Spain, the Royal Decree 376/2022 regulates the guarantees of origin of renewable gases.[63] The producer of hydrogen from renewable sources must be recorded in the register of renewable production plants, and must be able to redeem guarantees of origin for the electricity used during hydrogen production. The Ministry for the Ecological Transition and the Demographic Challenge issued Order TED/1026/2022, which establishes the procedure for managing the system of guarantees of origin for gas from renewable sources.[64] Additionally, Circular 1/2018 of 18 April, issued by the Spanish Markets and Competition Commission (CNMC), further regulates the administration of the guarantees of origin system for electricity from renewable energy sources.[65]

[61] CertifHy, *Towards a New Hydrogen Market: CertifHy Green Hydrogen Guarantees of Origin Are Launched* (CertifHy, 2020) https://www.certifhy.eu/sin-categoria/towards-a-new-hydrogen-market-certifhy-green-hydrogen-guarantees-of-origin-are-launched/ accessed 18 February 2025.

[62] European Commission, *Renewable Hydrogen* (2023) https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen/renewable-hydrogen_en accessed 18 February 2025.

[63] Royal Decree 376/2022 of 17 May, regulating sustainability criteria and the reduction of greenhouse gas emissions for biofuels, bioliquids, and biomass fuels, as well as the system for guarantees of origin for renewable gases (BOE No 118, 18 May 2022) https://www.boe.es/diario_boe/txt.php?id=BOE-A-2022-7840 accessed 18 February 2025.

[64] Order TED/1026/2022 of 28 October, approving the procedure for the management of the system of guarantees of origin for gas from renewable sources (BOE No 261, 29 October 2022) https://www.boe.es/diario_boe/txt.php?id=BOE-A-2022-17428 accessed 18 February 2025.

[65] Circular 1/2018 of 18 April, issued by the Spanish Markets and Competition Commission (CNMC), establishing the methodology for managing the system of guarantees of origin for electricity from renewable energy sources and high-efficiency cogeneration (BOE No 98, 24 April 2018) https://www.boe.es/diario_boe/txt.php?id=BOE-A-2018-5451 accessed 18 February 2025.

In 2023 the US Department of Energy (DOE) adopted the Clean Hydrogen Production Standard (CHPS) establishing a target of 4.0 kg CO_2e per kg H_2 for life cycle greenhouse gas emissions associated with hydrogen production.[66] This standard aligns with the goals of the Bipartisan Infrastructure Law[67] and the Inflation Reduction Act (2021), which aims to promote the production of clean hydrogen from diverse energy sources.[68]

Additionally, Japan's strategy includes developing certification systems for hydrogen produced from renewable energy.[69]

These certification systems are critical in providing legal certainty for the development of a transparent and trustworthy renewable and low-carbon hydrogen market. Notably, ISO/TS 19870:2023 plays an important role in standardizing the measurement of greenhouse gas (GHG) emissions across various hydrogen production paths. By providing a transparent and consistent benchmark for evaluating hydrogen's environmental impact, it promotes investor confidence, allows for fair competition between hydrogen production methods based on their GHG footprint, and aids in the certification of sustainable hydrogen.

Finally, international cooperation is crucial for addressing the legal challenges in hydrogen development. The Hydrogen Council, a global industry coalition, advocates for harmonized regulations and standards. The International Energy Agency's (IEA) Hydrogen Technology

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66 US Department of Energy, *Clean Hydrogen Production Standard (CHPS)* (2023) https://www.energy.gov/eere/fuelcells/articles/clean-hydrogen-production-standard-chps-guidance accessed 18 February 2025.

67 Bipartisan Infrastructure Law, Pub L No 117-58, 135 Stat 429 (2021).

68 Inflation Reduction Act of 2022, Pub L No 117-169, 136 Stat 1818 (2022).

69 Ministry of Economy, Trade and Industry (METI, Japan), *Hydrogen Policy Subcommittee Report* (6 June 2023) https://www.meti.go.jp/shingikai/enecho/shoene_shinene/suiso_seisaku/pdf/20230606_5.pdf accessed 18 February 2025.

Collaboration Programme promotes global cooperation in hydrogen research and development. Hydrogen development faces significant legal challenges, from regulatory uncertainty to IP disputes and liability concerns. Thus, addressing these challenges through international cooperation, standardisation, and clear regulations is crucial for the growth of the hydrogen industry.

4. TRENDS IN THE DEVELOPMENT OF HYDROGEN

With the global energy landscape undergoing a significant transformation, hydrogen is emerging as a vital component of the transition to a low-carbon economy. Moreover, as concerns about climate change, air pollution, and energy security continue to grow, the development of hydrogen technologies is accelerating, driven by innovations in production, storage, transportation, and utilisation. This part of the article explores the latest trends in hydrogen development, examining the technological, infrastructural, and market advancements that are shaping the future of this versatile energy carrier.

- *Electrolysis Technologies*: Electrolysis is the process of using electricity to split water into hydrogen and oxygen, offering a promising method for producing green hydrogen.[70] This process is now at the forefront of trends in hydrogen development. There is no doubt that recent technical breakthroughs in electrolysis have made relevant technologies more efficient, cost-effective, and scalable.[71] The main types of emerging electrolysis technologies include proton exchange membrane (PEM) electrolysis, alkaline electrolysis, and solid oxide

[70] Mamoon Rashid and others, 'Hydrogen Production by Water Electrolysis: A Review of Alkaline Water Electrolysis, PEM Water Electrolysis and High Temperature Water Electrolysis' (2015) 4(3) International Journal of Engineering and Advanced Technology 80-93.

[71] Mostafa El-Shafie, 'Hydrogen Production by Water Electrolysis Technologies: A Review' (2023) 20 Results in Engineering 101426.

electrolysis.[72] Electrolysis technologies have improved significantly, with increased efficiency, reduced costs, and enhanced durability. These technologies have various applications, including in relation to green hydrogen production, power-to-x (P2X) solutions, industrial processes, and transportation fuel.[73]

The benefits of electrolysis technologies include zero emissions, abundant resource (water), flexibility and scalability, and improved energy security.[74] Despite the advancements, challenges remain, such as cost reduction, system integration, and infrastructure development. Future research for hydrogen development should focus on materials, scientific advancement, system optimisation, and large-scale deployment. Electrolysis technologies are poised to transform the hydrogen landscape, offering a cleaner, more sustainable alternative. As research and development continue, we can expect even more efficient, cost-effective, and scalable solutions to emerge. The future of hydrogen development looks bright, and electrolysis technologies are leading the charge.

- *Water impact assessments:* environmental impact assessments are a key means of managing the environmental impacts of green hydrogen projects, and specifically, water impact assessments. One of the best known environmental impacts of green hydrogen production is its consumption of large volumes of water for electrolysis —around 9 liters of water per kilogram of green

[72] Mamoon (n 32).
[73] Tingjun Zhan and others, 'Application of Electrolysis Water Production in the Field of Renewable Energy Power Generation' (2020) 598 IOP Conference Series: Earth and Environmental Science 012088.
[74] Ömer Akay and others, 'Electrolysis in Reduced Gravitational Environments: Current Research Perspectives and Future Applications' (2022) 8 npj Microgravity 56.

hydrogen produced.[75] In areas with water scarcity or stress, this demand can affect local water resources and compete with other water consumers, particularly if there are multiple green hydrogen projects in the area. [76]

Ensuring sustainable water sourcing will be paramount to mitigate the environmental impacts of green hydrogen production. Some emerging thinking in this line inclines towards the utilization of non-freshwater sources, like seawater or treated wastewater, to minimize competition with fresh water resources. [77] However, these alternative water sources require desalination or treatment technologies, which are also energy-intensive. In coastal or arid regions, desalination is often required to provide water for electrolysis. Desalinization increases the energy consumption of green hydrogen projects, and could lead to CO_2 emissions if fossil fuels are used to power this process. Therefore, tackling the water-energy nexus in green hydrogen projects is key to ensuring its sustainability.

- *Finance:* Hydrogen projects face significant financial challenges, particularly due to high initial investment costs and market uncertainties. To address these obstacles, in 2022 the European Commission established the European Hydrogen Bank as part of the REPowerEU plan, which aims to reduce fossil fuel dependency and promote renewable hydrogen adoption across the EU.[78] Although not created through specific legislation, the bank is grounded in EU climate and energy policies that target climate neutrality by 2050. In its first pilot auction held in October 2023, the Hydrogen Bank

[75] G Squadrito, G Maggio and A Nicita, 'The Green Hydrogen Revolution' (2023) 216 *Renewable Energy* 119041 https://doi.org/10.1016/j.renene.2023.119041 accessed 18 February 2025.
[76] Ibid.
[77] Ibid.
[78] European Commission, *European Hydrogen Bank* (European Commission, 2022) https://energy.ec.europa.eu/topics/eus-energy-system/hydrogen/european-hydrogen-bank_en accessed 18 February 2025.

allocated €720 million to support seven projects, aiming to produce 1.58 million tonnes of renewable hydrogen over a decade and prevent more than 10 million tonnes of CO_2 emissions.[79] A second auction with a €1.2 billion budget was held in December 2024, proving the EU's commitment to closing the investment gap and de-risking hydrogen projects. The auction finished with funds allocated to a varied portfolio of renewable hydrogen initiatives spanning several member states, with an emphasis on large-scale electrolysis, cross-border infrastructure, and industrial decarbonization. This conclusion underscores the EU's deliberate commitment to speed up the implementation of green hydrogen technologies and improve energy resilience.[80] The result of the auction, including the selected projects and funding allocations, have since provided further clarity on EU's hydrogen investment strategy.[81]

- *Renewable Energy Integration*: Renewable energy integration is a new trend in hydrogen development, enabling the production of green

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[79] European Commission, 'Winners of First EU-Wide Renewable Hydrogen Auction Sign Grant Agreements, Paving the Way for New European Production' (European Commission, 7 October 2024) https://climate.ec.europa.eu/news-your-voice/news/winners-first-eu-wide-renewable-hydrogen-auction-sign-grant-agreements-paving-way-new-european-2024-10-07_en accessed 18 February 2025; Hydrogen Europe, 'European Hydrogen Bank Pilot Auction Results Spark Renewable Hydrogen Competitiveness' (Hydrogen Europe, 30 April 2024) https://hydrogeneurope.eu/european-hydrogen-bank-pilot-auction-results-spar

[80] European Commission, 'Second Renewable Hydrogen Auction: European Commission Publishes Terms and Conditions' (27 September 2024) https://climate.ec.europa.eu/news-your-voice/news/second-renewable-hydrogen-auction-european-commission-publishes-terms-and-conditions-2024-09-27_en accessed 18 February 2025; Offshore Energy, 'Second European Hydrogen Bank Auction with €1.2 Billion Budget Is Officially Open' (3 December 2024) https://www.offshore-energy.biz/second-european-hydrogen-bank-auction-with-e1-2-billion-budget-is-officially-open/ accessed 18 February 2025; Reuters, 'EU Changes Hydrogen Project Auction Rules to Limit Chinese Presence' (27 September 2024) https://www.reuters.com/article/eu-hydrogen-projects-idUSL5N27H5AK accessed 18 February 2025.

[81] Offshore Energy, 'Second European Hydrogen Bank Auction with €1.2 Billion Budget Is Officially Open' (3 December 2024) https://www.offshore-energy.biz/second-european-hydrogen-bank-auction-with-e1-2-billion-budget-is-officially-open/ accessed 18 February 2025.

hydrogen.[82] This means that various renewable energy sources can power hydrogen production, including solar energy, wind energy, hydrokinetic energy, and geothermal energy. The challenges arise when integrating renewable energy with hydrogen production; these challenges include intermittency, energy storage limitations, infrastructural constraints, and cost.[83] There are several successful projects around the world that demonstrate the feasibility of renewable energy integration in hydrogen development, for example, Solar-Powered Electrolysis in Australia, Wind-Powered Hydrogen Production in Denmark, and Hydrokinetic Energy-Based Hydrogen Generation in the USA. Renewable energy integration is revolutionising hydrogen development, enabling the production of green hydrogen. Finally, while challenges persist, innovative solutions and successful implementation paves the way for a sustainable energy future, and we can expect even more efficient, cost-effective, and scalable renewable energy-hydrogen systems.

- *Transportation of Hydrogen and Storage*: Today, hydrogen can be transported via pipelines, tanker trucks, rail, ships, and containers. Each method has its advantages and disadvantages, and the choice depends on the specific application and location. Major hydrogen storage developments include Compressed Hydrogen Tanks, Liquid Hydrogen Tanks, Metal Hydride Storage, Carbon Fiber Reinforced Polymer (CFRP) Tanks, and Underground Storage. The advancements in storage and transportation technologies have improved safety, efficiency, and cost-effectiveness, leading to several benefits, such as reduced emissions, energy security, and

[82] Somtochukwu Godfrey Nnabuife, 'Integration of Renewable Energy Sources in Tandem with Electrolysis: A Technology Review for Green Hydrogen Production' (2024) International Journal of Hydrogen Energy https://doi.org/10.1016/j.ijhdene.2024.06.342.
[83] Qusay Hassan and others, 'Renewable Energy-to-Green Hydrogen: A Review of Main Resources, Routes, Processes, and Evaluation' (2023) 48(46) International Journal of Hydrogen Energy 17383-17408.

diversification of the energy mix.[84] Even yet, important hurdles include infrastructure development, cost reduction, safety issues, and energy efficiency. Nonetheless, successful initiatives have shown the viability of hydrogen transportation and storage. For example, Fluxys' Belgian hydrogen pipeline network demonstrates how existing natural gas infrastructure may be modified for hydrogen transport, therefore contributing to regional energy security and cross-border connectivity. These include the Hydrogen Pipeline Network in Germany, Liquid Hydrogen Transportation in Japan, and Compressed Hydrogen Storage in the USA. In going forward, there is a need for a committed research focus dedicated to the improvement of infrastructure development, storage materials, energy efficiency, and cost reduction strategies.

- *Fuel Cell Technologies*: Fuel cell technologies are transforming the hydrogen landscape, offering a clean, efficient, and reliable energy solution.[85] These technologies, such as Proton Exchange Membrane (PEM) Fuel Cells, Solid Oxide Fuel Cells (SOFCs), Alkaline Fuel Cells (AFCs), Phosphoric Acid Fuel Cells (PAFCs), and Molten Carbonate Fuel Cells (MCFCs), have different benefits, including zero emissions, high efficiency, reliability, flexibility, and quiet operation.[86] Fuel Cell Electric Vehicles in Japan, Stationary Fuel Cells in the United States, and Portable Fuel Cells used by the US military for mobile power production in remote or tactical locations all indicate significant advances in fuel cell technologies. While

[84] Miao Yang and others, 'A Review of Hydrogen Storage and Transport Technologies' (2023) 7(1) Clean Energy 190-216.
[85] Huije Zhou and others, 'Understanding Innovation of New Energy Industry: Observing Development Trend and Evolution of Hydrogen Fuel Cell Based on Patent Mining' (2024) 52 International Journal of Hydrogen Energy 548-560.
[86] Manish Kumar Singla, 'Trends So Far in Hydrogen Fuel Cell Technology: State of the Art' (2019) 8(4) International Journal of Advanced Trends in Computer Science and Engineering 1146-1155.

challenges, such cost reduction, infrastructure development, durability, and scalability persist, innovative solutions and successful examples of implementation pave the way for widespread adoption. Therefore, as research continues, we can expect even more efficient, cost-effective, and scalable fuel cell technologies to emerge.

- *Hydrogen Infrastructure Development*: Recent developments in hydrogen infrastructure reflect both increasing demand and regulatory interventions aimed at facilitating a transition to low-emission alternatives. While global hydrogen consumption is rising, it remains largely confined to traditional sectors such as refining and chemical production, with supply still predominantly reliant on unabated fossil fuel-based hydrogen.[87] A critical regulatory challenge lies in shifting existing hydrogen applications toward low-emission alternatives while integrating hydrogen into new sectors, including heavy industry and long-distance transport, in line with emissions reduction targets.[88] Governments have responded by enacting policies and allocating public funds to support hydrogen infrastructure, recognizing its role in energy security and decarbonization. Concurrently, private sector investment in hydrogen infrastructure has intensified, influenced by regulatory incentives and expanding market opportunities. The proliferation of national and international policies, alongside increasing public and private investment, underscores a broader commitment to establishing hydrogen as a viable energy source within the evolving regulatory landscape.
- Challenges to Repurposing Fossil Fuel Infrastructure for Hydrogen: One proposed strategy to hydrogen transportation and storage is to use existing oil and natural gas infrastructure. Retrofitting these

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[87] IEA, 'Global Hydrogen Review 2023' (2023) https://www.iea.org/reports/global-hydrogen-review-2023 accessed 23 July 2024.

[88] BE Lebrouhi, 'Global Hydrogen Development: A Technological and Geopolitical Overview' (2022) 14(11) International Journal of Hydrogen Energy 7016-7048.

systems, however, necessitates substantial effort and technological adjustments due to hydrogen's unique qualities. Unlike oil and natural gas, hydrogen provides unique technical issues, such as the need for liquid storage at extremely low temperatures (-253°C), which necessitates the use of specific materials and containment technology. Furthermore, hydrogen's potential to produce metal embrittlement corrodes pipelines and storage facilities over time, creating worries about long-term infrastructure integrity. These issues limit the practicality of converting fossil fuel infrastructure to hydrogen usage, necessitating careful regulatory and economical considerations.[89]

- *Global Cooperation and Agreements:* The development of hydrogen has become a focal point of international collaboration, with countries and organizations establishing agreements and initiatives to accelerate its adoption.[90] For example, in 2021, the United Nations Industrial Development Organization (UNIDO), with support from the governments of Austria, China, Germany, and Italy, launched the Global Programme for Hydrogen in Industry to help developing countries overcome barriers to a sustainable hydrogen economy. That same year, UNIDO and the Government of China established the International Hydrogen Energy Centre (IHEC) to support the creation of hydrogen value chains and focus on research, development, and demonstration of key hydrogen technologies.[91] More recently, in February 2024, the Global Environment Facility (GEF) approved the UNIDO Global Clean Hydrogen Programme, a

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[89] A Sadeq, R Homod, A Kadhim and others, 'Hydrogen Energy Systems: Technologies, Trends, and Future Prospects' (2024) 939 *Science of The Total Environment* 173622 https://doi.org/10.1016/j.scitotenv.2024.173622.
[90] World Economic Forum, 'Global Collaboration Boosts Green Hydrogen and Could Spur More Green Energy Partnerships' (2023) https://www.weforum.org/agenda/2023/09/global-collaboration-boosts-green-hydrogen-and-could-spur-more-green-energy-partnerships/ accessed 23 July 2024.
[91] AV Gabov and MS Lizikova, 'Hydrogen Energy: Legal Support and International Cooperation' (2022) 92 Herald of the Russian Academy of Sciences S612-S626.

five-year initiative aimed at launching national clean hydrogen projects in eight countries while creating a global knowledge-sharing platform. Additionally, the Green Climate Fund Readiness Programme, launched by UNIDO at the end of 2023, is a two-year initiative designed to strengthen South Africa's institutional capacity to coordinate hydrogen activities outlined in its Hydrogen Society Roadmap.[92] Beyond UNIDO-led efforts, several bilateral and multilateral agreements have emerged. Namibia and the European Union have entered into multiple hydrogen-related agreements, including the Get Transformed project and various collaborations under the GH Programme and the Environmental Investment Fund, aimed at fostering Namibia's green hydrogen sector. UNIDO has also partnered with organizations such as the International Renewable Energy Agency (IRENA), Hydrogen Europe, and the Slovene Enterprise Fund to drive global hydrogen development.[93]

5. CONCLUSION

This article has examined hydrogen development, focusing in particular on current challenges and trends in the sector. The development of hydrogen as a clean energy source faces a complex array of legal challenges and opportunities. While regulatory frameworks, IP issues, liability concerns, and international cooperation pose significant hurdles, current trends in electrolysis technologies, renewable energy integration, storage and transportation innovations, fuel cell advancements, infrastructure expansion, and emerging business models demonstrate the industry's potential for growth and transformation.

[92] UNIDO, 'UNIDO's GEF-8 Global Clean Hydrogen Programme' https://www.unido.org/news/unidos-gef-8-global-clean-hydrogen-programme.

[93] European Commission, 'Global Gateway: EU and Namibia Agree on Next Steps of Strategic Partnership on Sustainable Raw Materials and Green Hydrogen' https://ec.europa.eu/commission/presscorner/detail/el/ip_23_5263.

Even as the world transitions to a low-carbon economy, addressing the legal challenges and capitalising on the trends in hydrogen development will be crucial for unlocking its full potential. By fostering international cooperation, standardisation, and clear regulations, we can overcome legal barriers and unleash the power of hydrogen to drive a sustainable energy future. The successful development of hydrogen as a clean energy source will ultimately require a coordinated effort from governments, industry players, innovators and lawyers to navigate the legal landscape and harness the technology's vast potential. By working together, we can create a hydrogen-powered future that is sustainable, efficient, and environmentally conscious.

Today, it is clear that there are multiple pathways to producing hydrogen, each with its own set of advantages and challenges. Moving forward, it will be important to continue researching and developing these different methods to increase the efficiency and sustainability of hydrogen production. Whether through centralized or distributed production, hydrogen has the potential to play a key role in the transition to a cleaner energy future. By exploring and supporting new technologies and advancements in the field, we can work towards developing and implementing a more sustainable and environmentally friendly energy source.