

# Hydrogen: A Game-Changer in Energy Sector and Path to Sustainability

**Hatem Mohamed Abdelazim**

Head of Economic Research, Asharqia Chamber, Kingdom of Saudi Arabia

[hatem.abdelazim@hotmail.com](mailto:hatem.abdelazim@hotmail.com)

الهيدروجين: مغيّر لقواعد اللعبة في قطاع الطاقة  
وطريق نحو الاستدامة

**حاتم محمد عبد العظيم**

رئيس البحوث الاقتصادية بغرفة الشرقية، المملكة العربية السعودية

[hatem.abdelazim@hotmail.com](mailto:hatem.abdelazim@hotmail.com)

- DOI: [10.21608/ijppe.2025.363267.1134](https://doi.org/10.21608/ijppe.2025.363267.1134) URL: [http://doi.org/ 10.21608/ijppe.2025.363267.1134](http://doi.org/10.21608/ijppe.2025.363267.1134)
- Received: 24/02/2025, Accepted: 28/04/2025, Published: 27/10/2025
- Citation: Abdelazim, Hatem. (2025). Hydrogen as a Game Changer in the Energy Sector: A Path Toward Sustainability. The International Journal of Public Policies in Egypt, 4(4), 194 - 215.

## **Hydrogen: A Game-Changer in Energy Sector and Path to Sustainability**

### **Abstract**

This study explores the potential of hydrogen as a transformative force in the global energy sector, highlighting its role in mitigating climate change, enhancing energy security, and supporting sustainable economic development. Using a qualitative review approach, this synthesis combines evidence from academic literature, policy reports, and international case studies, with a thematic focus on the technical, financial, and policy dimensions of hydrogen. The analysis covers global developments with particular attention paid to emerging markets and developing economies (EMDEs), drawing primarily on studies published between 2018 and 2024 to reflect recent technological and policy advancements. The findings indicate a growing international interest in hydrogen; however, low-carbon hydrogen remains underutilized, accounting for less than 1% of total production. This study is limited by its reliance on secondary sources and its qualitative synthesis. This emphasizes the need to bridge financial, policy, and technological gaps, especially in EMDEs, through increased investment, refined policy mechanisms, and enhanced international cooperation. Future research should incorporate empirical studies, regional analyses, and quantitative modeling to strengthen the understanding of hydrogen deployment pathways.

**Keywords:** Hydrogen energy, green hydrogen, blue hydrogen, low-carbon economy, energy transition

## Introduction

The global energy sector faces an urgent need to reconcile continued economic development with the imperative to reduce greenhouse gas (GHG) emissions. While conventional fossil fuels still account for the majority of global carbon dioxide emissions, mounting climate pressure and energy security concerns have increased the demand for cleaner and more sustainable alternatives. Therefore, hydrogen has emerged as a versatile, low-carbon solution that can simultaneously address multiple challenges. Its applications range from decarbonizing heavy industries to powering zero-emission vehicles and positioning hydrogen at the forefront of next-generation energy strategies.

However, despite the potential of hydrogen, its current global production remains heavily reliant on fossil fuels, rendering truly low-emission hydrogen as a small fraction of the total supply. Scaling up the production of green hydrogen requires substantial financial resources, policy support, and technological innovation, which can be particularly challenging in emerging and developing economies (EMDEs). These regions possess significant renewable capacity for generating green hydrogen, but often lack the necessary infrastructure, capital, and policy frameworks to realize their full benefits.

Considering these complexities, this study undertakes a qualitative review of the evolution of the hydrogen industry and its broader implications for the energy system. Specifically, it explores the role of hydrogen in advancing net-zero targets, with special emphasis on bridging the gap between theoretical promises and practical implementation in EMDEs. By synthesizing insights from academic literature, industry reports, and international case studies, this study highlights the key drivers of hydrogen adoption as well as the persistent barriers in financing, technology, and governance that must be overcome for hydrogen to become a viable global energy carrier.

The main objective of this study is to analyze how hydrogen can be scaled up effectively, particularly in EMDEs, to serve as a significant enabler of a low-carbon transition. To fulfill this objective, the following research questions were posed.

- 1- What are the primary drivers and barriers influencing hydrogen adoption across different regions and sectors?
- 2- How can emerging markets and developing economies overcome financial, policy, and infrastructural obstacles in producing and deploying low-emission hydrogen?
- 3- Which key policy instruments, collaborative frameworks, and investment models are most effective in accelerating the global uptake of hydrogen, particularly in green hydrogen production?

The remainder of this paper is structured into nine sections. Section two reviews the literature on the role of hydrogen in decarbonization, technological advances, policy frameworks, financial aspects, definitions, and challenges for emerging markets and developing economies. Section three describes the qualitative methodology and thematic analysis. Section four highlights the applications of hydrogen in transportation, power generation, and industry. Sections five and six examine global

demand and supply trends, respectively. Section seven addresses policy frameworks and public–private initiatives, while Section eight discusses investment needs through 2030, focusing on EMDEs. Section nine concludes the paper with key findings, policy recommendations, limitations, and future research directions.

### **Literature Review**

This part is divided into seven sections as follows:

#### **Overview of Hydrogen's Role in Decarbonization**

Hydrogen is increasingly being recognized as a key component of global strategies aimed at achieving net-zero emissions, given its potential to replace fossil fuels in sectors that are difficult to electrify, such as heavy industry and long-haul transportation (IEA, 2024a). However, current hydrogen production is predominantly derived from fossil fuels, particularly natural gas, which results in significant greenhouse gas emissions. Green hydrogen, produced via electrolysis using renewable electricity, offers a low-carbon alternative but currently accounts for less than 1% of global hydrogen production owing to cost and scalability challenges (IRENA, 2022).

#### **Technological Advances and Barriers**

Recent technological advancements in electrolysis, storage solutions, and fuel cells have significantly improved the viability of hydrogen as an energy carrier. Electrolyzer efficiency has improved, and production costs have declined sharply, yet substantial hurdles remain, including high initial investment costs and efficiency losses during energy conversion processes (Hydrogen Council, 2023). Additionally, infrastructure deficits such as limited hydrogen refueling stations and underdeveloped distribution networks present considerable barriers to their widespread adoption (BloombergNEF, 2024).

#### **Policy and Regulatory Frameworks**

Policy frameworks play a pivotal role in facilitating hydrogen market expansion. Several nations, notably within the European Union, Japan, and South Korea, have introduced ambitious hydrogen roadmaps and incentives, including subsidies, carbon pricing, and targeted investment programs (European Commission, 2023). However, regulatory uncertainty, particularly regarding safety standards, certification of low-carbon hydrogen, and international trade regulations, continues to impede private-sector engagement and cross-border hydrogen commerce (IEA, 2024a).

#### **Economic and Financial Considerations**

Investment in a hydrogen infrastructure requires significant capital. IRENA (2022) estimates that annual investments in hydrogen must increase up to sixfold to meet international climate targets by 2030. Despite growing investor interest, financing remains constrained by perceived risks, long payback periods, and policy uncertainties, particularly in developing economies where financial markets are less mature (World Bank, 2024). Blended finance mechanisms, public-private partnerships, and innovative risk mitigation tools have been proposed as effective means of mobilizing necessary capital (Climate Policy Initiative, 2023).

### **Definition and Types of Hydrogen Energy**

As a part of the literature review, it is important to first clarify the definition and main types of hydrogen energy.

As an alternative to fossil fuels, hydrogen energy offers a potentially cleaner way to power the world. Two main types have been highlighted (McKinsey & Company, 2024).

#### ***Green Hydrogen (GH<sub>2</sub>)***

It is the production of hydrogen from renewable energy sources, such as solar and wind energy, through electrolysis, a process that splits water into hydrogen and oxygen using electricity. Unlike blue hydrogen, GH<sub>2</sub> is cleaner and more sustainable (ATCO Ltd., 2025).

GH<sub>2</sub> is a fuel for the future because of its cleanliness, storability, and ability to be transported over long distances. When combined with oxygen, it burns to produce water and heat without releasing dioxide. Its high energy density makes it ideal for powering energy-intensive industrial processes and as a raw material for various industrial applications. In addition, as a clean energy carrier, GH<sub>2</sub> can be stored for extended periods with minimal loss. Unlike grid-connected renewable electricity, electricity can be transported more flexibly over long distances to applications farther from renewable energy sources (IRENA, 2020).

#### ***Blue Hydrogen***

It is a low-carbon energy source that is created through the steam reforming of natural gas. This process captures the emitted carbon dioxide (CO<sub>2</sub>) and reuses it or stores it. However, some experts caution that long-term CO<sub>2</sub> storage without a reliable leak prevention mechanism is not feasible (ATCO Ltd., 2025).

Blue hydrogen, generated from fossil fuels and carbon capture and storage (CCS), can serve as a catalyst for establishing a hydrogen market during the early stages of energy transition. This approach would simultaneously reduce greenhouse gas emissions while leveraging the existing infrastructure (Shell, 2025).

Promising blue hydrogen presents several challenges. It relies on limited resources, making it vulnerable to fluctuations in fossil fuel prices. Additionally, it involves the costs and complexities of transporting and storing CO<sub>2</sub>, which undermine energy security. Moreover, the efficiency of CCS, the technology used to capture CO<sub>2</sub>, remains suboptimal, resulting in residual emissions. Furthermore, the use of methane in CCS can lead to leakage, rendering blue hydrogen incompatible for achieving net-zero emission targets (Faisal et al., 2022).

### **Hydrogen in Emerging Markets and Developing Economies (EMDEs)**

While literature covers hydrogen development in advanced economies, few studies have focused on the potential and challenges of hydrogen within EMDEs. Despite abundant renewable energy resources, these regions typically encounter substantial hurdles, including financial barriers, weak institutional capacities, inadequate infrastructure, and limited technological expertise (UNCTAD, 2022). Thus, a critical gap exists in understanding how tailored financial models, supportive policy

environments, and technology transfer mechanisms can facilitate hydrogen deployment in EMDE contexts (World Economic Forum, 2025).

### **Critical Gaps Identified**

The existing body of literature predominantly emphasizes technical feasibility and market readiness within developed economies, and frequently overlooks the unique constraints and opportunities faced by EMDEs. Studies often lack comprehensive analyses of financial frameworks and policy instruments specifically designed for these regions, resulting in limited practical guidance for stakeholders interested in hydrogen investment and adoption in developing markets (Hydrogen Council, 2023; UNCTAD, 2022).

Consequently, this study aims at bridging these gaps by focusing on hydrogen deployment pathways in emerging economies. It explores innovative financial structures, policy strategies, and international collaboration models that can effectively accelerate the uptake of green hydrogen and related infrastructure, aligned with global decarbonization objectives.

### **Research Methodology**

This study employed a qualitative methodology designed as a comprehensive literature review and thematic analysis, systematically synthesizing data from secondary sources. A qualitative approach was selected to critically evaluate the current state of knowledge regarding the role of hydrogen in global energy transition, with particular attention paid to emerging markets and developing economies (EMDEs). Given the complexity and multidisciplinary nature of hydrogen applications, as well as related policy and financial considerations, a qualitative methodology provides the necessary flexibility and depth to thoroughly explore interconnected issues.

### **Research Design and Approach**

This study employed a structured literature review framework, utilizing a thematic analysis approach. The review process involves the collection and systematic evaluation of existing literature and relevant policy documents from reputable organizations, such as the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA), the Hydrogen Council, the World Economic Forum (WEF), the World Bank, and peer-reviewed academic journals. Thematic analysis was employed to identify patterns, recurrent issues, barriers, and drivers associated with hydrogen deployment across various sectors and geographic regions.

### **Data Collection**

Data was collected through comprehensive research conducted in scholarly databases, including Scopus, Web of Science, Google Scholar, and official websites of relevant international organizations. Specific keywords and phrases, such as "green hydrogen," "blue hydrogen," "hydrogen financing," "hydrogen policies," "renewable hydrogen in developing economies," "hydrogen infrastructure," and "hydrogen investment barriers," guided the search strategy. The literature selected for inclusion in this study primarily covers publications and reports issued between 2019 and 2024,

ensuring the inclusion of the most recent developments, technological advancements, and policy frameworks related to hydrogen.

### **Inclusion and Exclusion Criteria**

Publications were included based on their relevance to the research objectives and questions, with a focus on hydrogen deployment in the context of climate mitigation, technological readiness, financial investment, and policy strategies. Priority was given to studies and reports that addressed barriers to and opportunities for hydrogen deployment, particularly within the EMDE context. The literature that provided empirical data, case studies, and in-depth policy analyses was specifically targeted for detailed review. Sources lacking sufficient relevance, credibility, or clarity, as well as those with an exclusive focus on purely technical aspects without implications for financial or policy frameworks, were excluded from the detailed analysis.

### **Data Analysis**

The collected literature was analyzed using thematic analysis. Initially, documents were reviewed to identify broad thematic categories relevant to hydrogen adoption, such as technical barriers, financing challenges, infrastructure constraints, and policy environments. Subsequent analyses involved detailed categorization, coding, and interpretation of the findings within each thematic category. Special attention was paid to comparative insights between developed and developing economies, focusing explicitly on identifying the unique gaps and challenges facing EMDEs. This analytical approach allowed the identification of critical research gaps and a nuanced understanding of the multifaceted issues affecting the potential of hydrogen as a global energy solution.

### **Scope and Limitations**

This study's geographic scope is global, with a specific emphasis on emerging and developing economies. The temporal boundary spans recent developments from 2019 through projections to 2030, aligned with international climate targets and energy transition roadmaps. Given the nature of the methodology, this study was limited by its reliance on secondary sources. The primary data was not collected. Although extensive efforts have been made to include comprehensive and updated data, the rapidly evolving nature of hydrogen technology and policy frameworks may limit the temporal relevance of some findings.

In summary, by employing a robust qualitative review methodology and thematic analysis framework, this study aims to provide critical insights into the ongoing scholarly and policy discussions surrounding the deployment and integration of hydrogen into the global energy transition, highlighting the necessary conditions and actionable pathways toward accelerated adoption in EMDEs.

### **Applications of Hydrogen Energy**

Hydrogen energy, often hailed as the cornerstone of a sustainable future, has applications in various sectors, including transportation, electricity generation, and industrial processes. As the global community is striving to reduce greenhouse gas emissions and transition to renewable energy

sources, hydrogen has emerged as a versatile and environmentally friendly alternative. In this comprehensive exploration, we delve into the multifaceted applications of hydrogen energy, examining its role in driving innovation, fostering economic growth, and mitigating the impacts of climate change (World Hydrogen Energy Organization, 2025).

### **Transportation**

Hydrogen fuel cell technology is revolutionizing transportation by providing zero emissions, quick refueling, and extended driving ranges compared with conventional engines and battery-powered vehicles. Fuel-cell vehicles (FCVs) harness hydrogen to generate electricity, thereby reducing air pollution and enhancing their energy security.

#### **Passenger Vehicles**

Hydrogen fuel cell passenger cars offer a clean and efficient alternative to gasoline vehicles, providing comparable performance and convenience. Automakers are expanding the availability of FCVs, making sustainable mobility accessible to a wide range of consumers.

#### **Commercial Vehicles**

Hydrogen fuel cells provide an effective solution for decarbonizing heavy-duty vehicles, including trucks and buses. They possess high energy density and the ability to refuel rapidly, which significantly reduces operating costs, mitigates urban air pollution, and contributes to achieving climate goals.

### **Electricity Generation**

Hydrogen plays a crucial role in the transition to clean energy production. It supports the generation of clean electricity, helps balance grids, and complements intermittent renewable energy sources, such as solar and wind. By ensuring grid stability, hydrogen contributes to the sustainable meeting of growing energy demands.

#### **Fuel Cell Power Generation**

Hydrogen fuel cells convert chemical energy into electricity with remarkable efficiency and minimal emissions. They are particularly suitable for distributed energy systems, backup power generation, and off-grid applications, and contribute significantly to the advancement of renewable energy adoption.

#### **Combined Heat and Power (CHP)**

CHP systems utilize hydrogen fuel cells to simultaneously generate electricity and heat, achieving an impressive efficiency of over 80%. This innovative approach not only reduces emissions but also lowers energy costs and enhances the system's resilience.

### **Industrial Processes**

Hydrogen enables cleaner and more efficient industrial operations spanning manufacturing and chemical production. Hydrogen supports sustainable industrial growth by reducing emissions, optimizing processes, and conserving resources.

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**Ammonia Production**

Renewable hydrogen provides a carbon-free pathway for ammonia production, which is crucial for fertilizers. Adopting this approach can significantly reduce the environmental impacts of agriculture and foster sustainable farming practices.

In the context of petroleum refining, greening the oil industry is essential for achieving a more sustainable future. By adopting renewable energy sources and eco-friendly technologies, we can reduce greenhouse gas emissions and mitigate the negative environmental impacts of oil production.

**Petroleum Refining**

The use of hydrogen in refining processes to remove impurities and produce high-quality fuels has been further improved by cutting-edge technologies, thereby reducing its environmental impact and increasing efficiency.

**Metal Processing**

Hydrogen, which is a clean reducing agent, plays a pivotal role in metal processing, particularly in steelmaking. Hydrogen contributes to sustainable industrial practices by reducing energy consumption, enhancing yields, and minimizing emissions.

**Research and Development**

Ongoing research and development are unlocking novel hydrogen technologies encompassing advanced materials and innovative production methods. These endeavors are being undertaken with the intention of revolutionizing energy systems and catalyzing the growth of the hydrogen economy.

**Advanced Materials**

Innovations in materials science have revolutionized the production, storage, and utilization of hydrogen. Advancements in catalysts and storage materials significantly enhance efficiency and reduce costs, thereby expanding the potential of hydrogen.

**System Integration**

Efforts to integrate hydrogen into existing energy systems are progressing rapidly. Researchers, policymakers, and industry stakeholders collaborate to scale up hydrogen infrastructure, ensure compatibility, and lay the groundwork for a hydrogen-powered future.

**Global Demand for Hydrogen Energy**

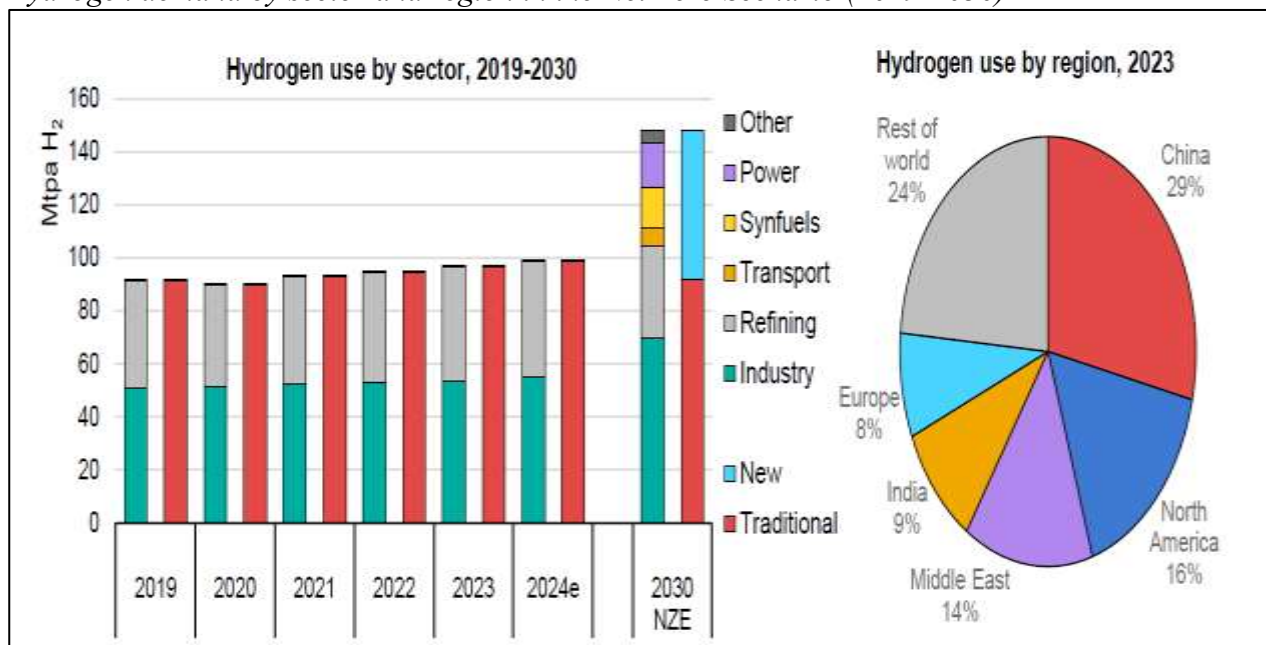
Global hydrogen demand surged to 97 million tons in 2023, a 2.5% increase from the previous year. Demand is primarily concentrated in the refining and chemical sectors and is largely fueled by hydrogen produced from unabated fossil fuels. As in previous years, low-emission hydrogen has played a negligible role, with production amounting to less than 1 million tons by 2023. However, according to the IEA Global Hydrogen Review, low-emission hydrogen production could reach 49 million tons annually by 2030, based on announced projects. This projection represents a substantial increase of nearly 30% compared with the current level.

This remarkable growth has been primarily driven by electrolysis projects with capacities exceeding 520 GW. In addition, the number of projects that have secured a Final Investment Decision (FID) is increasing. Notably, announced production that has secured FID has doubled compared to last year, reaching 3.4 Mtpa. This represents a significant five-fold increase in production compared to current levels by 2030. The distribution of this growth is roughly balanced between electrolysis (1.9 Mtpa) and fossil fuels, with carbon capture, utilization, and storage (CCUS) (1.5 Mtpa) (IEA, 2024b).

The regional distribution of hydrogen demand has remained largely unchanged since 2022. China, the largest hydrogen user, accounted for nearly one-third of the global demand, and approximately 28 Mt, which is more than double that of the second-largest user, the United States, which accounted for 13 Mt, representing 14% of the global demand. Hydrogen demand experienced modest growth in all major regions, except for the Middle East, where growth was significantly higher, exceeding 6% year-on-year. This growth can be attributed to an increase in demand for refining and methanol production. India has also witnessed substantial growth, with a year-on-year increase of more than 5% driven by a surge in demand for refining and the steel sector (IEA, 2024a). Refer to Figure 1 for further details.

**Figure 1**

*Hydrogen demand by sector and region in the Net Zero Scenario (2019-2030)*



Source: (IEA, 2024a).

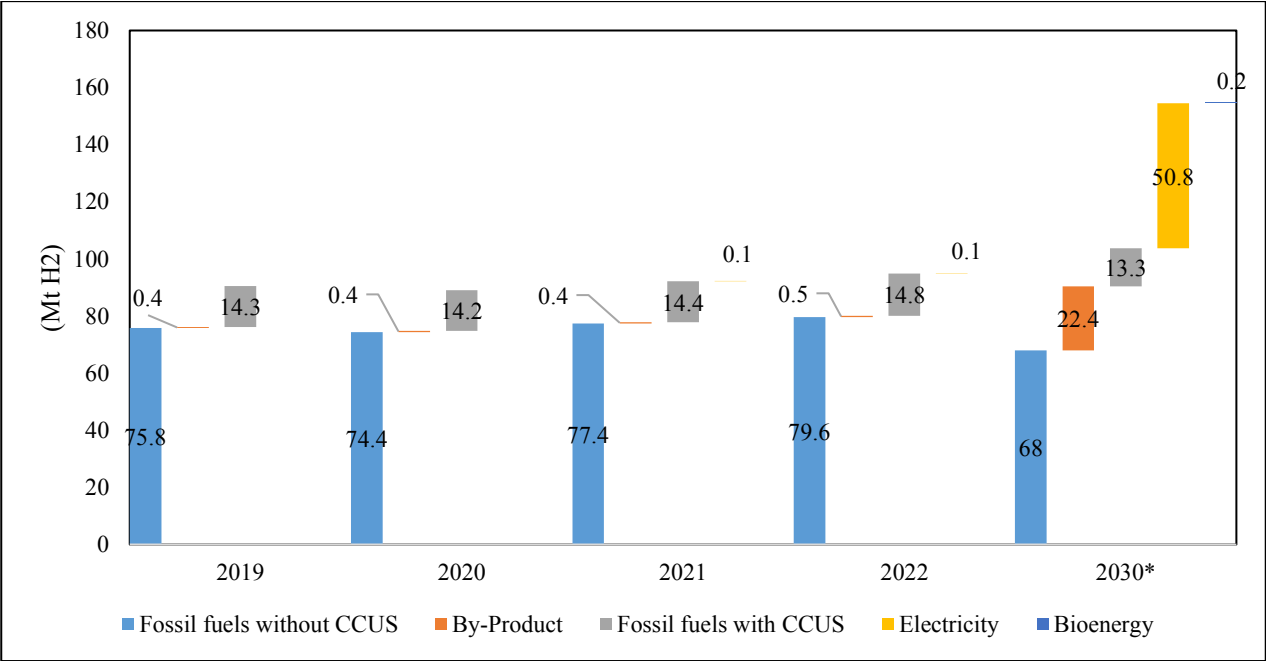
### Global Supply of Hydrogen Energy

Currently, dedicated hydrogen production relies heavily on fossil-fuel technologies. Approximately a sixth of the global hydrogen supply originates from “by-product” hydrogen,

primarily in the petrochemical industry. In 2023, natural gas accounted for nearly 66.6% of the energy required for dedicated hydrogen production, whereas coal contributed approximately 20%. Notably, China, which alone accounts for 90% of global coal consumption for hydrogen production, utilizes coal in its hydrogen production processes.

Low-emission hydrogen production accounted for less than 1% of the total hydrogen production in 2023, despite a 6% increase from the previous year. This growth can be attributed to the addition of 700 MW of electrolysis capacity and more than 10 kt H<sub>2</sub>/year production capacity from natural gas with CCUS and biomass, mainly from the Prince George refinery project in Canada. Refer to Figure 2 for further details.

**Figure 2**  
*Global hydrogen production by technology in the Net Zero Scenario, 2019-2030*



2030\*: Estimated values. CCUS = Carbon capture utilization and storage.

Source: (IEA, 2025).

Figure 2 reveals that hydrogen production from fossil fuels without carbon capture, utilization, and storage remains the leading technology in the field. In 2019, it accounted for approximately 83.7% of the market, and its share increased to around 83.9% in 2022. Although projected to decline to 44% by 2030, it will still maintain the top spot in terms of the technology employed. Electrochemical processes in the industry occupy the second position, with a share of approximately 15.9% in 2019 and 15.6% in 2022. However, it is anticipated to drop to fourth place by 2030. Electricity-based hydrogen production is expected to secure the second position by 2030, with a share of around 32.8%. Conversely, hydrogen production from fossil fuels with carbon capture, utilization, and storage is projected to rank third, with a share of approximately 14.5% by 2030.

According to the International Energy Agency-IEA (2024a), the hydrogen supply surged by 2.5% by 2023, reaching 97 million tons of hydrogen (H<sub>2</sub>). Primarily, this growth was driven by domestic production within industrial hubs, with minimal international trade contributing to the supply. China is a leading producer, accounting for approximately 30% of the global total. The United States and the Middle East are closely behind, each contributing 14% of the global production. India also makes a significant contribution, accounting for 9% of the global total. The agency projects that global production will continue to expand to meet the growing demand.

### **Policies Announced for the Implementation of Hydrogen Energy**

Global commitment to hydrogen as a critical element of the energy transition has led to an increasing number of countries establishing national hydrogen strategies. By 2024, 19 governments had published new hydrogen strategies, predominantly in emerging markets and developing economies (EMDEs). These strategies highlight a collective focus on decarbonization, energy security, domestic industrial growth, and export opportunities. Notably, these strategies prioritize domestic industry expansion over hydrogen imports, instead focusing on the potential for domestic industry growth and export development (IEA, 2024a).

European countries such as Austria, Belgium, Croatia, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Italy, Lithuania, Luxembourg, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Spain, Sweden, and the United Kingdom have articulated explicit hydrogen roadmaps to foster renewable and low-carbon hydrogen production. For instance, Germany's National Hydrogen Strategy, updated in 2023, emphasizes green hydrogen as a central element of its climate-neutrality goal, with clear funding mechanisms and international cooperation initiatives. Denmark's PtX tender, which supports over 280 MW of electrolysis, has become a model for successful competitive bidding and policy execution. These roadmaps typically involve substantial public funding, competitive bidding for hydrogen projects, and clear regulatory frameworks to incentivize hydrogen deployment (IEA, 2024a; Council of the European Union, 2024; Danish Energy Agency, 2023; UK Department for Energy Security & Net Zero, 2023).

In Asia, nations such as China, India, Japan, South Korea, Singapore, and Turkey have also introduced national strategies that emphasize green hydrogen to facilitate the transition to low-carbon energy systems. South Korea's Hydrogen Economy Roadmap has led to the construction of over 100 hydrogen refueling stations and hundreds of fuel-cell buses across major cities by 2023. India's National Green Hydrogen Mission is expected to attract significant private investment and enable a global hydrogen export market. These efforts highlight significant governmental initiatives aimed at scaling hydrogen production capacities and supporting infrastructure (IEA, 2024a).

In the Americas, Argentina, Brazil, Canada, Chile, Colombia, and the United States have similarly launched strategies to accelerate renewable hydrogen production by focusing on developing hydrogen hubs and enhancing market competitiveness. Chile's National Green Hydrogen Strategy has positioned the country as the future top three global exporter, supported by favorable geography and international partnerships. For instance, the US National Clean Hydrogen Strategy and Roadmap

emphasizes significant federal investment in establishing hydrogen production facilities, infrastructure, and related technological innovations (United States Federal Register, 2024).

African countries, such as Egypt, Mauritania, Morocco, Namibia, and South Africa, have outlined strategies specifically geared toward leveraging their abundant renewable resources to position themselves as global exporters of green hydrogen. Namibia, for example, signed agreements worth over USD 10 billion in 2023 with international partners to develop hydrogen infrastructure, marking a breakthrough in green hydrogen investment in Africa. These strategies promote sustainable economic growth and regional energy security (IEA, 2024a).

In Oceania, Australia and New Zealand have advanced their hydrogen ambitions, with Australia updating its National Hydrogen Strategy in 2024 to align with broader decarbonization goals. Australia's Hydrogen HeadStart initiative commits over USD 2 billion to support large-scale hydrogen production projects, setting a global benchmark. New Zealand is developing its Interim Hydrogen Roadmap to explore its potential contributions to sustainability and economic diversification (IEA, 2024a).

Globally, governments have pledged nearly USD 100 billion in public funding for hydrogen initiatives by 2024. However, most of these funds were in the preliminary announcement stage, highlighting the need for concrete implementation actions. Advanced economies account for approximately 95% of these public funds, whereas emerging economies primarily rely on tax incentives rather than direct subsidies. This preference is often due to limited fiscal capacity and higher public debt levels in emerging economies, which constrain their ability to provide direct subsidies. Tax incentives offer a more manageable and flexible mechanism to attract private investment, while minimizing immediate government expenditure. Competitive bidding has been increasingly adopted as an effective mechanism to stimulate market formation and drive down hydrogen costs, with various incentive structures reflecting differences in national power markets and policy designs (IEA, 2024a; Danish Energy Agency, 2023).

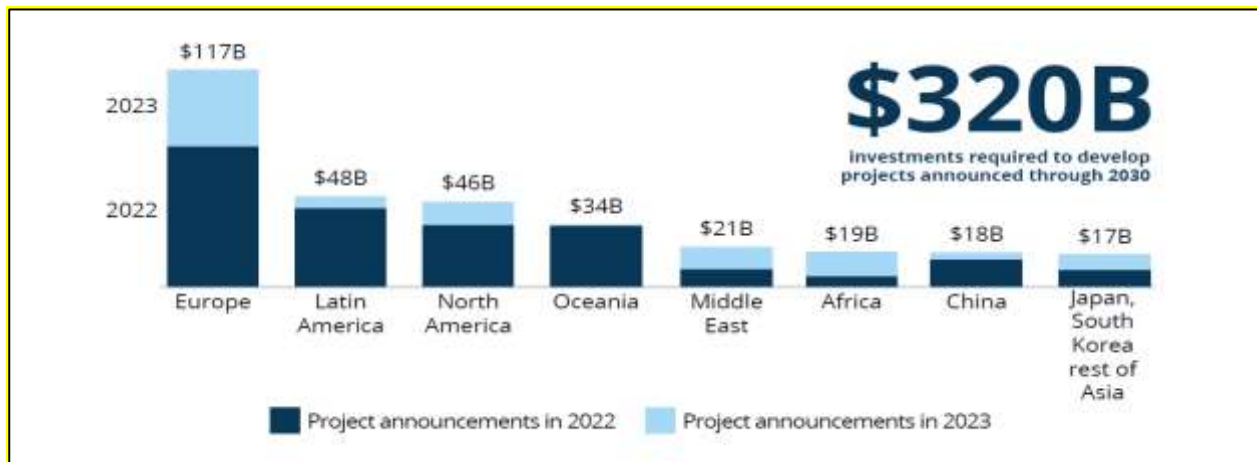
Governments worldwide have collaborated to define clear regulatory and certification frameworks for hydrogen. Examples include the United States' guidelines under the Inflation Reduction Act (IRA), the European Union's Hydrogen and Gas Decarbonization Package, and the United Kingdom's revised Low-Carbon Hydrogen Standard (Council of the European Union, 2024; UK Department for Energy Security & Net Zero, 2024).

### **Investments Required for Hydrogen Energy by 2030**

The number of renewable and low-carbon hydrogen production projects in pipelines has increased significantly, from 230 in 2022 to 435 in 2023. Notably, most of these projects (412) focused on producing renewable hydrogen, whereas only 23 prioritized low-carbon hydrogen. Additionally, approximately a quarter of all projects (115) were in emerging markets and developing countries (EMDCs), excluding China (see Figure 3).

**Figure 3**

*Investment needed to develop announced projects covering the hydrogen value chain through 2030 (billions of US dollars), and project investment volume growth (2020 – 2023)*

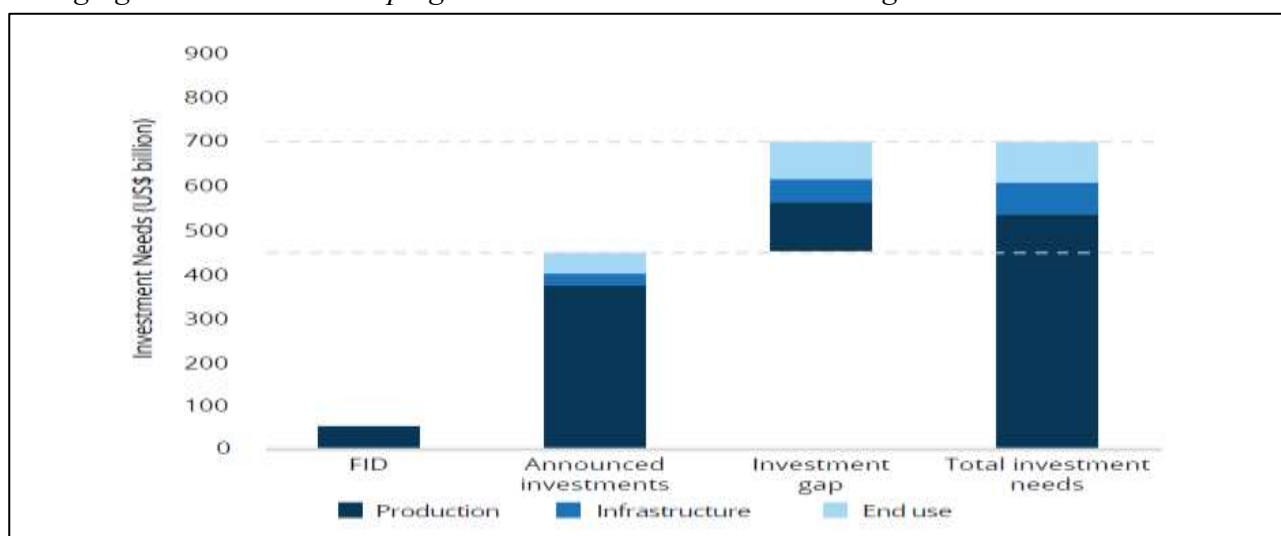


**Source:** (Organization for Economic Cooperation and Development (OECD), 2024).

The Hydrogen Council projects the global clean hydrogen production financing requirements between now and 2030 to be approximately USD 700 billion (excluding China and renewable power generation). However, only 4 % of the necessary capital has been committed so far. If renewable power generation is included, EMDC will need an investment of USD 700 billion between now and 2030, which equates to USD 100 billion annually. However, only a small portion of these projects has progressed to the investment decision stage.

**Figure 4**

*Emerging markets and developing countries' investment needs through 2030*



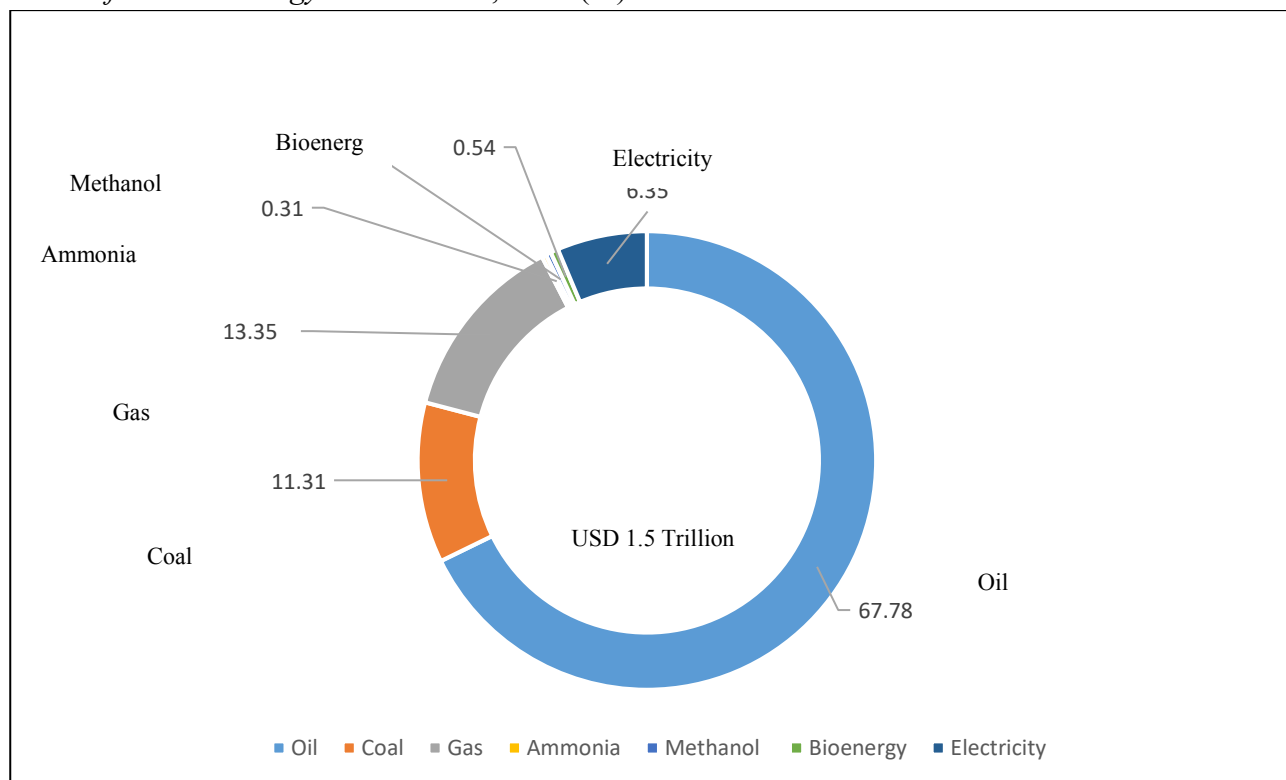
**Source:** (Organization for Economic Cooperation and Development (OECD), 2024).

Approximately 20 clean hydrogen projects in emerging markets outside China have progressed to the Final Investment Decision (FID) stage. A significantly larger number are in various stages of preparation, encompassing production processes, enabling infrastructure, and end-use projects. Among these projects, the most prominent and advanced is the USD 8.5 billion NEOM project in Saudi Arabia, which has successfully secured financial closure. Notably, Oman has recently concluded six agreements worth USD 20 billion with international developers to establish renewable hydrogen production facilities within its borders. Additionally, approximately 65 projects have been announced across the Middle East and North Africa (MENA) region. The World Bank is currently actively supporting deployment initiatives in over ten countries, including Brazil, Chile, India, Mauritania, and Namibia.

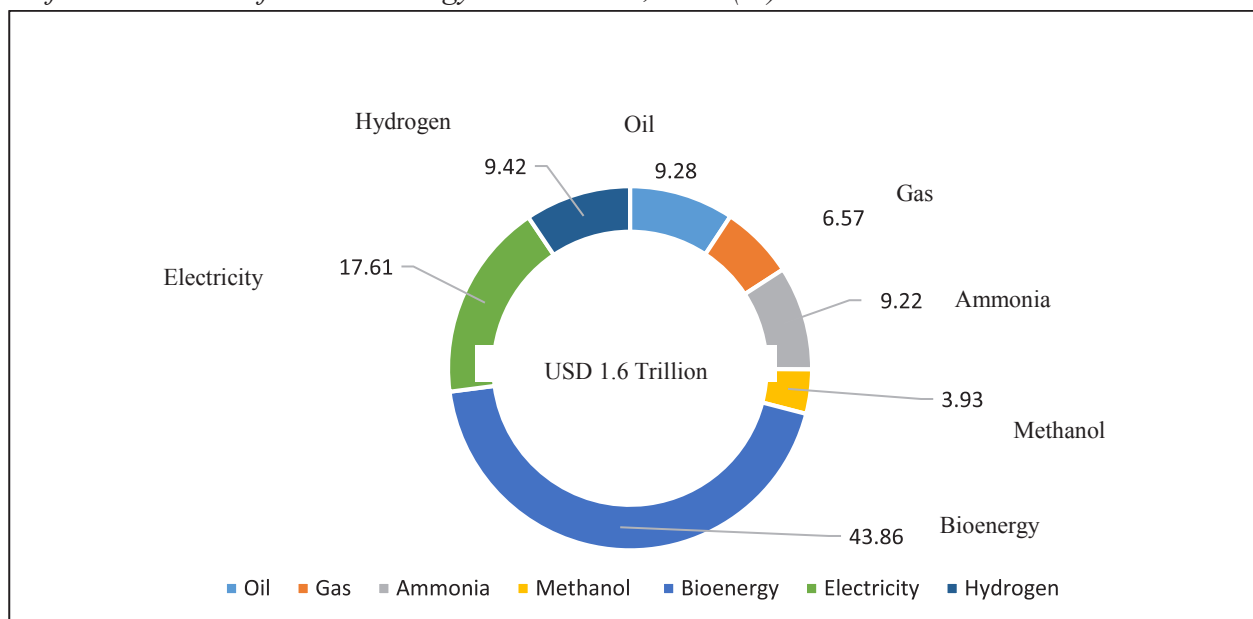
According to IRENA (2022), the hydrogen industry will be less competitive and lucrative than the oil and gas industry. Clean hydrogen does not generate returns comparable to those of oil and gas. Hydrogen is a conversion business, not an extraction business, and it has the potential to be produced competitively in various regions. This limits opportunities to capture economic rents, such as those generated by fossil fuels. Additionally, as the cost of green hydrogen decreases, new and diverse participants enter the market, further intensifying competition. (Refer to Figures 5 and 6 for more details).

**Figure 5**

*Value of trade in energy commodities, 2020 (%)*



**Source:** (IRENA, 2022).

**Figure 6***Shifts in the value of trade in energy commodities, 2050 (%)**Source:* (IRENA, 2022)

### Conclusion

The development of the hydrogen industry has marked a significant shift in the global energy sector, offering a promising path toward a low-carbon economy. Amidst the pressing challenges of climate change and energy security, hydrogen, particularly green hydrogen, has emerged as a versatile and sustainable energy source. This study delves into the substantial progress made in hydrogen energy generation, highlighting the distinction between green hydrogen, which harnesses renewable energy sources, and blue hydrogen, which utilizes natural gas with carbon capture and storage (CCS). While blue hydrogen can serve as a transitional solution, it falls short of aligning with long-term net-zero emission objectives owing to its reliance on fossil fuels and the complexities associated with CCS.

The global demand for hydrogen is surging, driven by its applications in transportation, electricity generation, and industrial processes. However, despite this growth, most hydrogen production still relies on fossil fuels, with low-emission hydrogen accounting for only 1% of the total production. To meet the ambitious targets set by the International Energy Agency (IEA) and other organizations, substantial investments in infrastructure, technology, and policy frameworks are imperative. Collaboration between governments and the private sector is crucial for scaling up hydrogen production, particularly in emerging markets and developing economies (EMDEs) where the potential for renewable hydrogen is substantial but largely untapped.

Furthermore, this study emphasizes the significance of policy support and funding mechanisms to bridge the cost gap between low-emission hydrogen and conventional fossil fuels. Although progress has been made, with 19 countries announcing new hydrogen strategies by 2024, the scale of

investment required to achieve net-zero goals remains substantial. The transition to a hydrogen-based economy necessitates not only technological advancements but also a coordinated global effort to ensure the viability and sustainability of hydrogen.

### **Recommendations**

- Prioritizing funding for green hydrogen projects in renewable-rich regions by scaling up electrolyzers and renewable infrastructure.
- Establishing clear and consistent regulations (subsidies, tax incentives, and carbon pricing) to close the cost gap with fossil fuels.
- Promoting international collaboration to share knowledge, technology, and best practices, particularly to benefit EMDEs.
- Investing in infrastructure for hydrogen storage, pipelines, distribution, and refueling stations, especially in transport.
- Expanding R&D funding for electrolyzers, fuel cells, CCS, and materials innovation to improve efficiency and lower costs.
- Encouraging public-private partnerships to de-risk investments, share costs, and accelerate deployment.
- Providing financial and technical support for EMDEs, including renewable energy projects, capacity building, and technology transfer.
- Establishing certification schemes and standards for low-emission hydrogen to ensure transparency and consumer confidence.
- Incentivizing hydrogen adoption in high-impact sectors, such as heavy industries, transport, and power generation.
- Implementing monitoring and evaluation mechanisms to track hydrogen progress, address challenges, and adjust strategies.

### **Limitations of the Study**

This study is limited by its reliance on secondary sources and a qualitative synthesis approach. While it draws on recent reports, policy documents, and academic literature, the absence of primary data restricts its ability to validate findings empirically. In addition, the rapidly evolving nature of hydrogen technologies and global policy frameworks may render some insights time-sensitive, thereby highlighting the need for continual updates.

### **Implementation and Beneficiaries**

The findings and recommendations of this study can inform policymakers, investors, and industry stakeholders engaged in the global energy transition. By providing a structured analysis of the opportunities and barriers to hydrogen, this study supports the design of targeted policies, financing mechanisms, and investment strategies. Beneficiaries include governments formulating hydrogen strategies, private sector companies seeking entry into hydrogen markets, and international organizations aiming at accelerating clean energy adoption, particularly in emerging and developing economies (EMDEs).

### **Future Research**

Future studies should complement qualitative reviews with quantitative and empirical analyses, such as techno-economic assessments, cost–benefit modeling, and scenario-based forecasting of hydrogen adoption. More detailed regional and sectoral studies are required, especially in EMDE contexts, to identify localized barriers and opportunities. Furthermore, research into innovative financing instruments, cross-border hydrogen trade mechanisms, and the socioeconomic impacts of large-scale hydrogen deployment would deepen understanding and support more effective policy implementation.

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Appendix

Table (1)  
*List of Abbreviations*

|                                 |                                          |
|---------------------------------|------------------------------------------|
| <b>CCS</b>                      | Carbon Capture and Storage               |
| <b>CCUS</b>                     | Carbon Capture, Utilization, and Storage |
| <b>CHP</b>                      | Combined Heat and Power                  |
| <b>CO<sub>2</sub> emissions</b> | Carbon Dioxide Emissions                 |
| <b>EMDs</b>                     | Emerging Market and Developing Economies |
| <b>FCVs</b>                     | Fuel-cell vehicles                       |
| <b>FID</b>                      | Final Investment Decision                |
| <b>GH<sub>2</sub></b>           | Green Hydrogen                           |
| <b>GHG</b>                      | Greenhouse Gas                           |
| <b>H<sub>2</sub></b>            | Hydrogen                                 |
| <b>MNA</b>                      | The Middle East and North Africa         |
| <b>R&amp;D</b>                  | Research and Development                 |

## الهيدروجين: مغير لقواعد اللعبة في قطاع الطاقة وطريق نحو الاستدامة

### المستخلص

تبحث هذه الدراسة في إمكانات الهيدروجين ليكون قوة محورية في تحول قطاع الطاقة العالمي، مع التركيز على قدرته في مواجهة تغير المناخ، وتعزيز أمن الطاقة، ودفع التنمية الاقتصادية المستدامة. ومن خلال منهجية مراجعة نوعية، تقوم الدراسة بتجميع نتائج من الأدبيات الأكاديمية، والتقارير السياسية، ودراسات الحالة الدولية، وتقدم تحليلاً موضوعياً للأبعاد التقنية والمالية والسياسية المتعلقة بالهيدروجين. وتغطي الدراسة النطاق الجغرافي العالمي، مع تركيز خاص على الأسواق الناشئة والاقتصادات النامية، وتعتمد على منشورات تمت بين عامي 2018 و2024، لتعكس التطورات التكنولوجية الحديثة وأطر السياسات المتغيرة. وتشير النتائج إلى وجود اهتمام عالمي كبير بالهيدروجين، إلا أن الهيدروجين منخفض الكربون لا يزال غير مستغل بشكل كافٍ، حيث يمثل أقل من 1% من إجمالي الإنتاج. وتخلص إلى التأكيد على ضرورة سد الفجوات المالية والسياسية والتكنولوجية، لا سيما في الاقتصادات النامية. وتوصي الدراسة بزيادة الاستثمارات، وتحسين آليات السياسات، وتعزيز التعاون الدولي، مما يوفر مساراً واضحاً لتمكين الهيدروجين من الإسهام بشكل كبير في إزالة الكربون على الصعيد العالمي. وتقتصر الدراسة أن تستكمل الأبحاث المستقبلية هذا التحليل من خلال دراسات تجريبية، وحالات إقليمية، ونماذج كمية لفهم أفضل لمسارات نشر الهيدروجين، خصوصاً في الاقتصادات الناشئة والنامية.

**الكلمات الدالة:** الطاقة المولدة من الهيدروجين، الهيدروجين الأخضر، الهيدروجين الأزرق، الاقتصاد منخفض

الكربون، التحول في مجال الطاقة