Unlocking Opportunities:

A Framework for Assessing Green Hydrogen Potential in Emerging Markets

April 2025

ESMAP
Energy Sector Management Assistance Program

IFC International Finance Corporation
WORLD BANK GROUP

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About ESMAP

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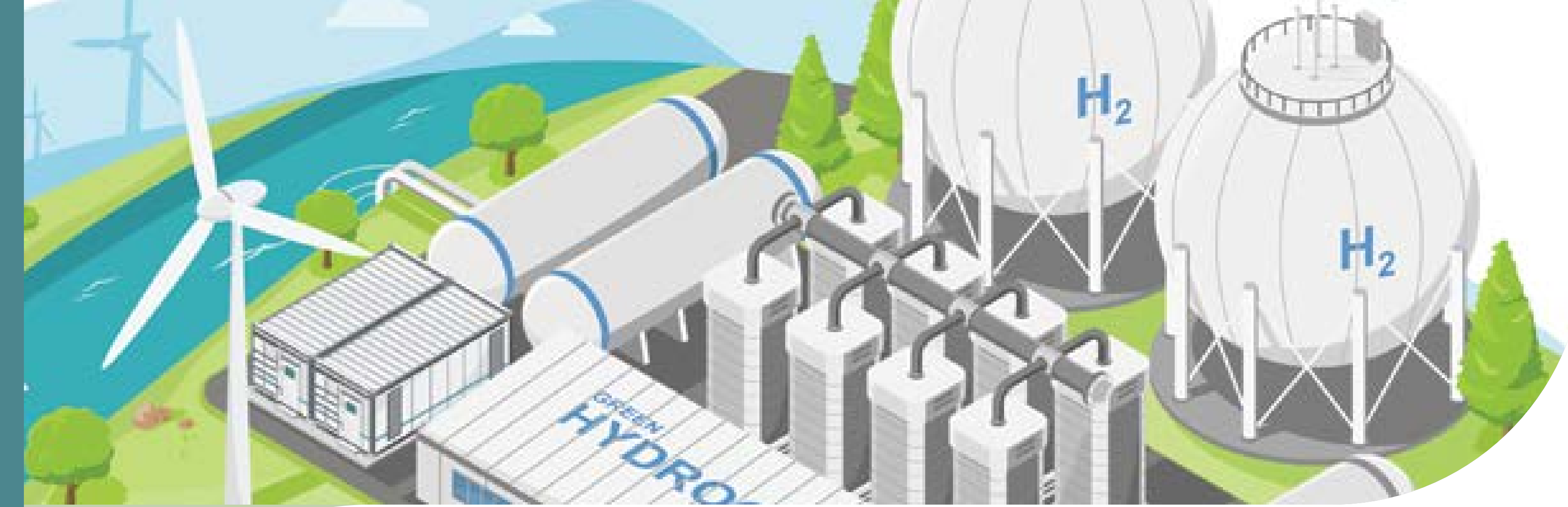

Foreword

Every decade in the energy sector seems to bring one new technology, and with it a novel asset category. Previous decades brought solar energy, wind energy, and then energy storage in the 2010s. Green hydrogen is the innovation for the 2020s. Green hydrogen has the potential of supporting renewable energy in a new form, which is useful in several industries that include but also reach beyond the energy sector. Green hydrogen provides three key differentiators compared to batteries as an energy storage medium: greater volume, easier transportability, and industrial use cases.

Whereas green hydrogen is a well-covered topic in general, there is still a dearth of analysis of its potential for emerging markets and of their characteristics. This report attempts to help close that gap. Some of the key actionable observations in the report are the criteria for assessing market readiness and the criteria for assessing project-level suitability.

A key finding is that green hydrogen is far from universally viable today. Markets and projects must be carefully selected. Wherever possible, the report uses case studies to illustrate its main points. Even though the report is concerned with emerging markets, it uses data and cases from developed economies because these are still leading indicators of what to expect. It then draws conclusions for emerging markets.

We recognize that this is a fast-moving field, and the data will surely evolve soon after publication of this report. However, we are confident that its findings will continue to hold. Overall, it should be a contribution to facilitating the efforts of developers, investors, and policy makers to bring green hydrogen and derivative projects more successfully to emerging markets. And that is IFC's goal: getting new clean energy asset categories to emerging markets faster.

Diep Nguyen-van Houtte
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Executive Summary

Green hydrogen is this decade's most significant innovation in energy. Green hydrogen could decarbonize heavy industries and long-distance transport while also providing development opportunities, which are especially critical in emerging markets. According to the International Energy Association (IEA), green hydrogen and derivative products, together with carbon capture, utilization, and storage, could account for one fifth of all emission reductions between 2030 and 2050. Over the past couple of years, there has been considerable progress in the innovation of clean energy technologies and government measures to promote their adoption. The increasing number of countries initiating national hydrogen strategies signals a long-term commitment to developing, designing, and deploying green hydrogen programs. However, green hydrogen deployment will take time to reach industrial scale since the technology and enabling environments necessary for projects remain nascent.

The World Bank has recognized the promise of green hydrogen, and its initial report on the potential impact of green hydrogen (H2) in emerging markets was released in August 2020, and since then, the energy sector has seen major shifts. The COVID-19 (Coronavirus) pandemic and the global energy crisis caused by Russia's invasion of Ukraine marked pivotal moments in the global energy dialogue. By the end of 2023, 52 countries had developed national hydrogen strategies, with more than 20 emerging markets establishing clear policies and frameworks to support early adopters. While political support for low-emissions hydrogen remains strong, implementation is still lagging.

In this publication, green hydrogen is defined as hydrogen produced from water electrolysis using renewable energy (RE) sources and low-carbon hydrogen is defined as hydrogen derived from fossil fuel processes whose emissions are reduced by carbon capture technology. Clean hydrogen or low-emission hydrogen, while not formal definitions, can refer to both green and low-carbon hydrogen.

The number of announced low-emission hydrogen production projects has grown rapidly, promising as much as 38 million metric tons annually by 2030 (27 million metric tons from renewable energy–powered electrolyzers), a figure 50 percent higher in 2023 than the International Energy Association (IEA) had estimated in 2022.[1] However, at the time of publication of this report, only 7 percent of this potential production has secured final investment decisions because of a confluence of factors,[2] including the following often-cited barriers that threaten a project's bankability: rising equipment, labor, and financing costs; supply chain disruptions (driven by the COVID-19 pandemic and the Russia's invasion of Ukraine); difficulty securing offtake agreements; insufficient demand-side incentives; the nascent scale of the electrolyzer industry; and uncertainty around policy implementation.

Focusing on hydrogen's potentially major role in meeting international energy and climate goals, governments in North America and Europe are introducing funding programs to support large-scale projects. However, the complexity of the sector and of the incentive programs, as well as the large risks and capital investments required, are contributing to implementation timelines that are slower than many proponents would like.

While electrolyzer deployment is picking up, so are the costs and challenges associated with water electrolysis systems. For example, the estimated costs for building a Western alkaline electrolysis system have increased by an average of 50 percent since 2022.[3] Key technologies have yet to be fully proven for large integrated projects operating with intermittent renewable power. To align with the Net Zero Emissions by 2050 Scenario, a significant acceleration in the expansion of electrolysis capacity is needed, requiring a surge to more than 550 gigawatts of installed capacity by 2030,[4] up from 3 gigawatts in 2023.

Current hydrogen demand is mainly for traditional uses, with low-emission hydrogen making up less than 1 percent. Hydrogen offtake is the key bottleneck limiting the scale-up of green hydrogen in the near term, as government targets for green hydrogen production far exceed demand from potential offtakers. The earliest profitable opportunities for green hydrogen will be its application in hard-to-abate industrial sectors, where it can replace hydrogen (and its derivatives) produced from fossil fuels.

Green hydrogen can play a crucial role in achieving net zero strategies, provided its production involves carbon-free energy and processes. While green hydrogen and its derivatives have the potential to decarbonize multiple sectors, it is essential to carefully evaluate alternative solutions within each sector to ensure two key objectives: (a) that hydrogen is used where it has the most significant impact on decarbonization considering strategies and policies at the national and global levels and cross-border collaboration; and, (b) that each sector is placed on the most competitive and efficient decarbonization pathway available taking into account the optimal technologies, infrastructure, systems, and mechanisms to reduce cost and incentivize sustainable production of green hydrogen. This strategic approach will maximize the benefits of green hydrogen and ensure the most efficient use of resources in transitioning to a low-carbon economy.

> Green Hydrogen is unique as a multi-role energy carrier that can impact multiple sectors.
>
> **The key challenge is its current high price.**
>
> Therefore,
>
> a. Its economic viability is not universal but differs between countries and industries.
>
> b. Policies must focus on reducing the cost of production
>
> c. Collaboration across markets can get to critical mass faster
>
> d. De-risking solutions need to stimulate demand

This report builds on the World Bank's recent Green Hydrogen in Developing Countries[5] and Scaling Hydrogen Financing for Development[6] publications, incorporating several key industry analyses and recent observations from the World Bank Group's experience.

The framework comprises the following chapters:

CHAPTER 1 underscores the rising role of green hydrogen in global climate efforts and its potential to drive development in emerging markets. It provides an overview of the market, technology, uses, and projections, as well as challenges and opportunities.

CHAPTER 2 outlines the primary barriers to scaling up green hydrogen production in emerging markets. The challenges include the current production cost gap between fossil fuel–produced hydrogen and green hydrogen, critical cost drivers, the discrepancy between the growing project pipeline and committed financing, and investor risk. It also discusses the significant roles of the private sector and standardization.

CHAPTER 3 DELINEATES crucial factors for establishing a successful green hydrogen market, emphasizing the importance of assessing a country's readiness for investments, with a focus on four main pillars: enabling environment, supply conditions, demand conditions, and the private sector ecosystem. It also offers case studies and insights into best practices.

CHAPTER 4 PROVIDES a detailed overview of key aspects in hydrogen projects, including technical, economic, and regulatory and environmental features; funding sources; project structures; and offtake risks. It further emphasizes the importance of comprehensive planning and proactive collaboration for successful implementation.

CHAPTER 5 provides a road map for leveraging hydrogen's transformative potential in clean energy transitions. It emphasizes tailored strategies, cross-border collaboration, robust infrastructure, efficient project development, adequate financial support, and supportive policies and incentives to foster market growth and innovation, thereby paving the way for emerging markets to play a role in building a sustainable energy future.

The discussion on green hydrogen markets and projects aims to guide stakeholders without imposing rigid directives or predetermined success metrics. Given the diversity of markets and projects—influenced by factors such as national agendas, available resources, and stakeholder dynamics—access to precise information at the project level is crucial for thorough opportunity assessment. As the global market progresses and projects transition from announcement to implementation, success indicators and significant criteria will evolve. Thus, the primary objective of this publication is to outline frameworks for evaluating the potential of green hydrogen markets while documenting best practices.

This report highlights the importance of a robust enabling environment, emphasizing clear strategies, government-backed investment mechanisms, cohesive regulations, and active private sector engagement. It also explores key aspects such as instruments and systems, regulatory frameworks, safety standards, and the role of international cooperation in shaping the green hydrogen landscape. Ultimately, this report underscores that there is no one-size-fits-all approach; countries must tailor their strategies to align with their unique strengths, priorities, and challenges to foster a thriving green hydrogen market.

1

Introduction

Green hydrogen has the potential to accelerate the clean energy transition. Green hydrogen could decarbonize heavy industries and long-distance transport while also providing development opportunities, which are especially critical in emerging markets. According to the International Energy Association (IEA), green hydrogen and derivative products, together with carbon capture, utilization, and storage, could account for one-fifth of all emission reductions between 2030 and 2050.[7] Over the past couple of years, there has been considerable progress in the innovation of clean energy technologies and government measures to promote their adoption. The increasing number of countries initiating national hydrogen strategies signals a long-term commitment to developing, designing, and deploying green hydrogen programs. However, green hydrogen deployment will take time to reach industrial scale since the technology and enabling environments necessary for projects remain nascent.

Today, hydrogen is commonly used in several industries, such as oil refining, chemicals, and fertilizers, yet less than 1 percent of the global hydrogen output is green. More than 95 percent of all hydrogen is produced from fossil fuels and biomass using the carbon-intensive thermochemical process. As of 2019, hydrogen production was responsible for 830 million tons of carbon dioxide per year ($MtCO_2$/yr), equivalent to the national emissions of Indonesia and the United Kingdom combined.[8] (Hydrogen definitions used in this publication are given in the end note.[9])

New technology adoption is expected to transition hydrogen production toward green methods, reaching maturity by 2030 and delivering its full market potential between 2030 and 2050. While the demand will continue to concentrate on traditional industrial applications, over time new uses of green hydrogen could overtake the refining and chemicals industry and could decarbonize other sectors such as mobility, iron, and steel, as well as heating and power.

An increase in the global demand for hydrogen tomorrow could be enabled by government mandates and incentives. The global demand for hydrogen reached 95 million metric tons in 2022, almost 3 percent more than in 2021, per IEA. By 2030, global demand for clean hydrogen is expected to exceed 6 million metric tonnes per annum enabled by government actions, including mandate implementation and incentive programs, to promote the adoption of clean hydrogen technologies.

The green hydrogen market is expected to experience significant growth, contributing to a broader shift toward clean hydrogen production. According to Global Market Insights, the global hydrogen market size surpassed $183 billion in 2022,[10] and is expected to reach $317 billion by 2032, expanding at an annual rate of 5.5 percent.[11] The share of the green hydrogen market is projected to expand from about $1 billion today to $30 billion in 2030.[12] Annual production of clean hydrogen could reach $112 billion in 2030 if all announced projects are realized.[13]

Green hydrogen is produced through water electrolysis powered by renewable energy. Green hydrogen and its derivatives promise to reduce greenhouse gas emissions in sectors that otherwise have few other technological options to decarbonize. Such hard-to-abate sectors as steel, cement, fertilizers, and heavy-duty transport can benefit from green hydrogen, which is well suited for fueling energy-intensive industrial processes difficult to electrify. Additionally, hydrogen is seen as an enabling technology and energy carrier that, when combined with renewables through long-duration energy storage, can help mitigate the intermittency of renewable energy sources. It can also extend the use of renewables in off-grid locations, as well as provide flexibility and peaking services during high electricity demand on the grid.

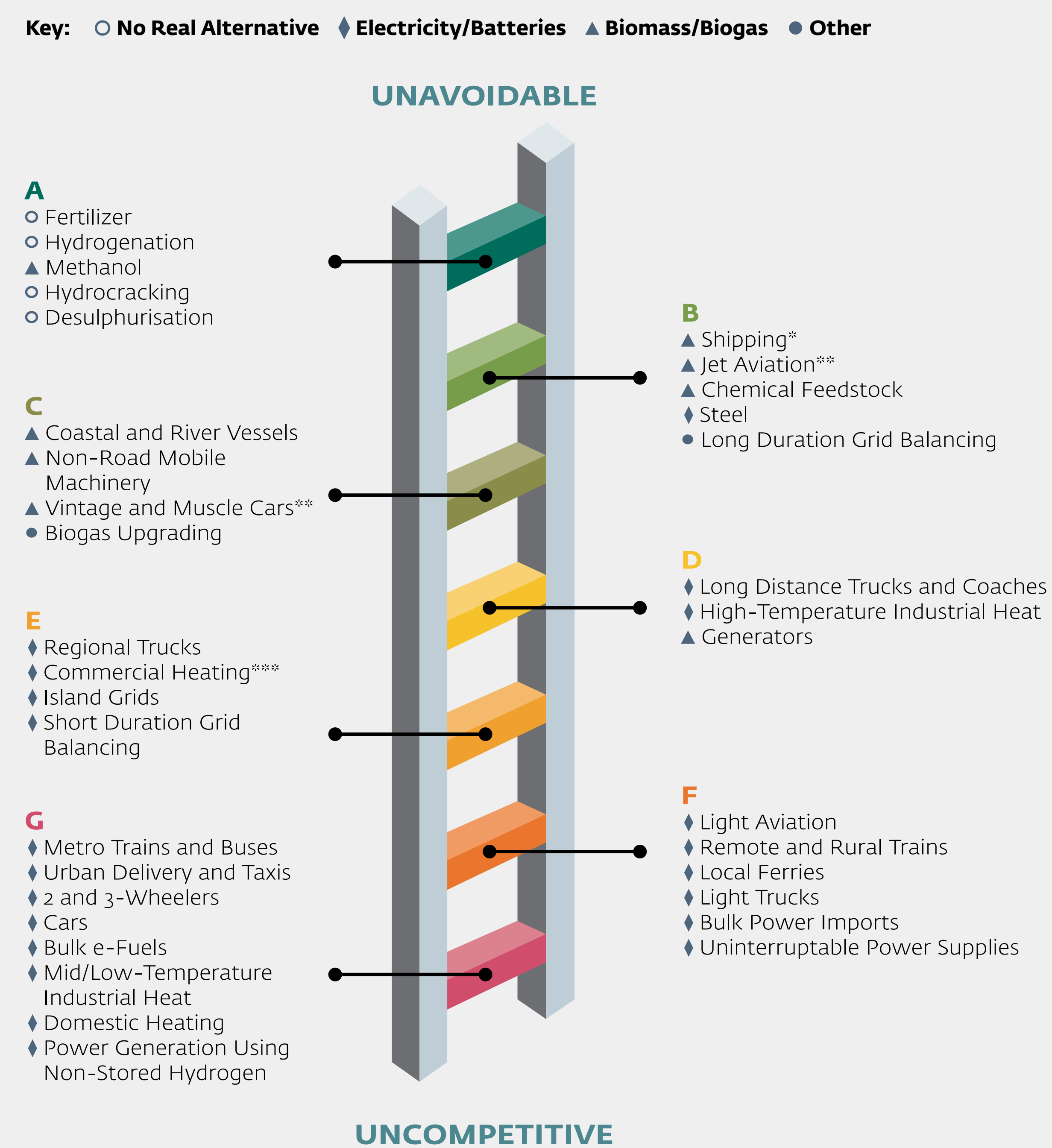
Blue, or low-carbon, hydrogen, which is produced by using natural gas coupled with carbon capture and storage, can be an initial catalyst during the early stages of energy transition from gray (fossil fuel hydrogen) to green. With blue hydrogen, greenhouse gas emissions from existing industrial processes can be temporarily reduced by using current infrastructure. However, blue hydrogen has several limitations, including residual methane emissions and inefficient use of resources due to the costs and monitoring of carbon transport and storage. Rapid transition to green through technological advances and cost declines in renewables and electrolyzers will further boost the attractiveness of green hydrogen applications. Technological risks also are associated with the capability of capturing carbon at this scale in an economically viable and sustainable manner.

Green hydrogen production investment opportunities face many challenges. The obstacles include significant technological barriers to producing green hydrogen, scaling-up of renewable energy generation and electrolyzer capacities, high production costs, lack of mature markets, limited infrastructure, and policy uncertainties. Countries and policy makers therefore need to create incentives to drive innovation, promote demand and supply, attract capital, and forge partnerships to reduce investment and market risks and stimulate green hydrogen production growth.

The current global resurgence surrounding green hydrogen centers largely on the perspective of the Global North. Early adopters' mission-driven policy making, such as the U.S. Inflation Reduction Act and the European Union's (EU's) implementation of industrial policies through mandates such as the Delegated Acts, has significantly shaped the attention toward the green hydrogen market on the global level. Key import hubs like Germany, Japan, and the Republic of Korea have forged numerous partnerships with developing nations, underscoring their pivotal role in international trade. While most early national hydrogen strategies originated in developed economies, an increasing

FIGURE 1.1

Liebreich Associates' Hydrogen Applications Ladder



Source: Michael Liebreich/Liebreich Associates, Clean Hydrogen Ladder, version 5.0, 2023. Concept credit: Adrian Hiel/Energy Cities. License at https://creativecommons.org/licenses/by/4.0/deed.en.

* As ammonia or methanol

** As e-fuel or power- and biomass-to-liquid fuel

*** As hybrid system

number of emerging countries are now joining the ranks planning to produce and use green hydrogen.

The private sector, driven by public sector commitments, is taking a strategic approach to investing in green hydrogen. Recognizing green hydrogen as one of the pathways to decarbonization, early movers are making long-term investments. They are forming partnerships along the value chain, even when the near-term cost competitiveness is not yet established. The private sector in industrialized countries is particularly active, exploring green hydrogen lead markets with promising end use applications. These uses span a wide range of sectors, including green ammonia and fertilizer, green steel, mobility, buildings, fuel cell trucking, oil refineries and petrochemicals, and green shipping, with the first profitable opportunities expected in local, close to the source of generation indus-trial use of hydrogen.

Figure 1.1 shows the Liebreich Associates' hydrogen ladder, which categorizes the most viable applications for hydrogen, ranking them from the highest value and most efficient uses to the least suitable. At the top are applications such as industrial feedstocks and heavy-duty transport, in which hydrogen's unique properties are essential. At the bottom are less competitive uses such as residential heating and light-duty vehicles, which are better served by direct electrification or other low-carbon alternatives. This ladder helps stakeholders prioritize hydrogen use where it can have an impact on decarbonization and economic feasibility.

Emerging markets can play a significant role in the global production of low-emission hydrogen while creating new opportunities for their economies. Countries with abundant low-cost resources, including renewable energy, desalinated or fresh water, infrastructure, and workforce, are well-positioned as export-oriented

TABLE 1.1.

Economics of Green Hydrogen by Application

	World Production, 2021 (megaton/year)	Product Price (US$/ton)	Green Product Price, 2030 (US$/ton)	Shipping Cost (Indicative) (US$/ton)	Energy Cost Benefit of Relocation (US$/ton)
Primary Aluminum	65	2,500	2,500	70-100	425
Ammonia	200	250-400	600	100	340
Cement	2,900	20	100	50	20
Iron	1,389	300-500	400-600	15-50	115
Jet Fuel	250	300-500	1000	50	600
Methanol	100	410-520	600	100	375
Hydrogen	120	800	1,500	**1,500**	**1,500**

Source: Dolf Gielen et al., "Renewables-Based Decarbonization and Relocation of Iron and Steel Making: A Case Study," *Journal of Industrial Ecology* 24, no. 5 (2020):1113–25.

Note: Energy cost benefits were calculated by multiplying energy intensity by cost savings per unit of energy. Shipping cost data is from recent surveys. Figures can fluctuate based on supply and demand. The energy cost benefit is US$0.03/kilowatt-hour for electricity, US$5/gigajoule for thermal energy, and US$1.5/kilogram for hydrogen. Mt= megaton; t = ton.

states in the global green hydrogen market **(table 1.1)**. Colocation or proximity to green hydrogen end users can provide significant economic benefits, especially when high transportation and shipping costs remain prohibitive. Countries can leverage green hydrogen production to strengthen their domestic economies, especially those with advanced industrial sectors. This strategy can minimize vulnerability to macroeconomic shocks from commodity price fluctuations; enhance energy security and affordability; decarbonize hard-to-abate sectors; and attract international capital, creating opportunities for collaboration and facilitating improved access to foreign currency through trade.

Several factors in addition to countries' cost of energy, infrastructure, industrial development, and international trade will influence investment decisions in green hydrogen. Political will translates into enabling policies and standards, starting with national hydrogen strategies and government incentives. Furthermore, international cooperation supports market development, while transparent and stable financial systems, along with private sector participation, facilitate the integration of green hydrogen into the domestic economy.

This report presents a framework for assessing green hydrogen investment opportunities in emerging markets. Given the dynamic business and policy environment for green hydrogen in emerging markets, and by summarizing the characteristics that make private sector investments in green hydrogen attractive at the country level, this framework can help benchmark opportunities, identify gaps, advance lessons learned, and provide actionable market intelligence for business development.

2

Green Hydrogen *in* Emerging Markets: Barriers *to* Scale

The main challenge to scaling up green hydrogen is simple economics. Fossil-produced hydrogen and its derivatives come at very low costs. Gray hydrogen is produced at as little as $1 to $2 per kilogram. Blue hydrogen, which includes the process of carbon capture, costs around $1.80 to $4.70 per kilogram. For comparison, in 2023 the levelized cost of green hydrogen production ranged on average between $4.50 and $12.00 per kilogram[14] (with the lowest cost of $2.50 to $3.00 per kilogram due to low-cost renewables), making green hydrogen largely uneconomical in today's market.

Three main variables affect green hydrogen production costs: (a) The cost of electricity is considered the major contributor to the overall green hydrogen cost, reaching more than 50 to 60 percent of production costs; (b) the cost of electrolyzers is the second largest share of total expenditure (30 to 35 percent[15]), which can vary depending on the technology used; and (c) the remaining share is attributed to operations and maintenance.[16] Additionally, these categories are split between capital expenditures (CAPEX) and operating expenditures (OPEX) (as outlined in **table 2.1**) and their influencing factors. A large portion of these costs is expected to fall because of technological advances, economies of scale, sector risk profile, and supportive policies. This topic is further discussed in chapter 3, pillar 2, which covers supply conditions, and is illustrated in box 2.1 **(case study 1)**.

FACTORS INFLUENCING CAPEX

- Cost and electricity reliability are key factors in selecting electrolyzer technology, ultimately affecting the overall CAPEX. If power cannot be sourced from an existing grid or is dependent on intermittent renewable energy, additional investments in battery or hydrogen storage systems may be required to ensure stable continuous operations.
- Project scale: Larger projects may benefit from economies of scale, potentially reducing the percentage share of certain categories. However, large-scale projects may depend on more advanced technology requiring higher up-front investment.

TABLE 2.1

Main Contributors to Green Hydrogen Production Costs

	Renewable Electricity	Electrolyzer	Operations and Maintenance
Total[a]	Renewable electricity accounts for more than 50% of the total cost of producing green hydrogen.	Electrolyzer capital expenditure and operations account for approximately 30% to 35% of the total cost.	Operations, maintenance, water, storage, transport, and "other" expenditures account for approximately 15% to 20% of the total cost.
CAPEX	**RE infrastructure: 30% of CAPEX** This includes the costs of setting up solar panels or wind turbines to provide the necessary renewable electricity for the electrolysis process. The exact share depends on scale and the local cost of renewable energy infrastructure and resource availability.	**Electrolyzers: 40% of CAPEX** Electrolyzers are a significant portion of the CAPEX due to the advanced technology and materials required. This percentage can vary with the type of electrolyzer (PEM, alkaline, or solid oxide) and country of manufacture.	**Site development and infrastructure: 30% of CAPEX** This category includes hydrogen storage, transport, and all auxiliary systems required for the electrolysis process, such as water supply and purification, power electronics, cooling systems, and other support infrastructure.
OPEX[b]	**Electricity costs: 55% of OPEX** Electricity, including electrolyzer utilization, is the largest component of OPEX for green hydrogen production since the electrolyzers require a significant amount of power to operate. The cost of electricity depends on the source (such as solar or wind) and market conditions.	**Maintenance and repairs: 20% of OPEX** Regular maintenance and repairs are crucial for keeping electrolyzers, renewable energy systems, and other infrastructure in good working order. This includes scheduled servicing, replacement of worn parts, and unscheduled repairs.	**Plant operations: 20-40% of OPEX** This category includes general maintenance, water supply, labor costs, insurance and safety, and other miscellaneous operational costs.

Source: Original table for this publication.

Note: CAPEX = capital expense; OPEX = operating expense; PEM = proton exchange membrane; RE = renewable energy.

a. All costs are approximate and vary depending on project design, location, and infrastructure.

b. Total OPEX costs average between 30% and 40% of CAPEX assumed over a project life cycle of 20 years, which is typical for infrastructure projects. Ratio of OPEX to CAPEX is calculated as OPEX per year times 20 years over CAPEX.

- Technology choice: The type of electrolyzer and storage method can significantly affect costs.
- Several electrolyzer technologies are at different stages of maturity and have varied price ranges, from approximately $600 per kilowatt for Chinese technologies to $2,500 per kilowatt for European technologies.
- While the electrolyzer cost curve is expected to decline over time, the price for large projects has been increasing in recent years, arising from higher balance of plant costs, engineering, procurement, and construction (EPC) costs, as well as other developer costs.
- Location: The cost of land, the availability of renewable energy, and the regulatory environment vary by region, influencing the overall CAPEX distribution.
- Innovation and efficiency improvements: Ongoing advancements in technology and efficiency can shift the cost distribution over time.
- Fluctuations in the cost of renewable electricity, depending on the country and the specific renewable energy source, can be a major factor in the overall cost.
- The cost of renewable electricity is projected to decline by 2030 and further by 2050, making green hydrogen significantly more economical over time.

FACTORS INFLUENCING OPEX

- Electricity prices vary significantly depending on the region, time of day, and type of renewable energy contract.
- Technological efficiency: More efficient electrolyzers and renewable energy systems can reduce electricity consumption and maintenance needs.
- Electrolyzer capacity factor balance: Costs are optimized on the basis of electrolyzer utilization and electricity costs.
- Scale of operation: Larger facilities may achieve economies of scale, reducing per-unit costs.
- Location: Costs for water supply, labor, and compliance can vary, depending on geographic location and local regulations.
- Automation: Increased automation can reduce labor costs but might increase maintenance and repair costs for the automated systems.

The cost of producing green hydrogen, depending on the region, is expected to decline to $2.50 to $4.00 per kilogram or less, driven by advancements in electrolyzer technology, manufacturing economies of scale, design improvements, and reduction in renewable energy cost. As of the writing of this report, one of the most competitive markets is considered to be Chile, where the levelized cost of electricity from new solar projects is now below 3 cents per kilowatt-hour. Reduced electrolyzer costs of up to 70 percent through 2050 are the strongest lever to bring down green hydrogen costs. However, further measures, such as the standardization of projects, are required to fully optimize green hydrogen production capital costs. While the decline in the cost of renewable electricity and electrolyzer technology could contribute to a 30 to 45 percent reduction in green hydrogen costs through 2030, the Hydrogen Council finds that active project optimization, such as bulk procurement and design simplification and standardization, could decrease these costs by an additional 25 percent.[17]

Besides the costs of green hydrogen production, the costs of transforming, transporting, and storing remain high. While emerging markets can enjoy cost competitiveness to produce green hydrogen, they may need to factor in storage and transportation costs to deliver green hydrogen to demand centers. The ability to transport and store hydrogen cheaply and easily would facilitate expansion of the hydrogen economy. For example, pipeline transport, considered the most cost-effective for distances between 1,000 and 5,000 kilometers, will cost an estimated $0.40 to $0.50 per kilogram of hydrogen, while for longer distances shipping becomes more cost-effective.[18] Moreover, limited competition in seaborne green hydrogen transport adds to costs.[19] Japanese Kawasaki Heavy Industries (KHI) is among the few companies with announced designs for liquefied hydrogen tankers expected to be commercial before 2030. The final price of hydrogen will be higher for importing countries such as Japan if ammonia is used as a carrier, because of the high-cost electricity needed to extract the hydrogen from the chemicals and because of the round-trip losses. Where feasible and for shorter distances, the cost of pipeline shipping via onshore or offshore pipelines can be considerably lower, though not without significant economic dependencies. Earlier projected cost estimates run at $0.18 per kilogram per 1,000 kilometers for new hydrogen transmission pipelines and $0.08 for retrofitted gas pipelines.[20] However, according to 2023 findings,[21] building new hydrogen infrastructure can be significantly more expensive than previously anticipated. Furthermore, green hydrogen transformations incur significant monetary and energy costs, undermining the overall efficiency relative to that of fossil fuels. Further studies are needed on the technical feasibility and costs.

Finally, the financing cost for green hydrogen developments can significantly affect a project's economic viability. Weighted average cost of capital can range from 6 to 24 percent or even higher in emerging markets, depending on factors such as the country risk profile, technology maturity, developer creditworthiness,

TABLE 2.2

Operational Electrolysis Projects in Emerging Markets

Country	Project Name	Year Commissioned	Electricity Source	Estimated Electrolyzer Input (MW)	Estimated Hydrogen Output (metric tons/year)
China	Sinopec 260MW Kuqa[a]	2023	Solar	260.00	20,000.00
South Africa	Sasol Sasolburg	2023	Wind + Solar	60.00	1,825.00
Brazil	EDP Port of Pecem	2022	Solar	1.25	64.26.00
Chile	HIF Haru Oni	2022	Wind	1.25	75.00
Egypt, Arab Rep.	Fertiglobe Egypt Green Hydrogen Pilot	2022	Wind + Solar	15.00	1,442.00
South Africa	Engie Mogalakwena Mine	2022	Solar	3.50	171.21
Chile	AngloAmerican Las Tortolas	2021	Solar	<1.00	<1.00

Source: Original table for this publication.

a. China's Sinopec, the world's largest green hydrogen facility, reportedly experienced early start-up problems due to Chinese electrolyzers operating at one-third of projected capacity. Recently, more and more technical issues have been reported by manufacturers or electrolysis asset owners, illustrating how immature the large-scale electrolyzer manufacturing industry still is today.

developer's track record, interest rates, tax rates, hydrogen-related policy incentives, and the debt-equity mix. Because of the high initial CAPEX, securing long-term financing and long-term hydrogen offtake agreements is crucial for economic feasibility, especially for projects in emerging markets. Government incentives, subsidies, and grants often play a significant role in reducing the financial burden and making projects more attractive to investors, especially in countries where high labor, infrastructure, and energy costs—coupled with prolonged approval processes—increase working capital demands. Additionally, public-private partnerships, blended concessional finance, and green bonds help mobilize the required capital while spreading risk. As the market matures, improved risk assessment and cost reductions in technology are expected to lower financing costs, further driving the scalability of green hydrogen projects.

The growth of the green hydrogen market has been slower than expected, despite ambitious climate goals and project commitments. In the IRENA World Energy Transitions Outlook 1.5°C Scenario, global hydrogen production would need to reach more than 600 million metric tons of hydrogen per year, or 12 percent of the global energy mix, by 2050. This would require $700 billion in total investments between 2023 and 2030 to finance clean hydrogen production, transport infrastructure, and end use equipment. Of that amount, as of early 2023, only $320 billion was announced and less than 10 percent ($29 billion) was committed as projects.[22]

The number of announced green hydrogen projects is growing, but the investment gap remains vast. In 2023, the global green hydrogen project pipeline grew by 35 percent to more than 1,400 large projects.[23] By 2030, the annual production of clean hydrogen is projected to reach 45 million metric tons. However, just 7 percent of the global announced capacity reached the final investment decision, and only 2 percent is under construction or operational.[24] While the reported additions of green hydrogen projects continue to increase, more is required to meet the climate goals: according to the Hydrogen Council, an additional $320 billion in new projects is needed by 2030,[25] as well as advancement of the announced early-stage projects to development.

As of late 2023, there were seven operational green hydrogen projects in emerging markets, located in Brazil, Chile, China, Arab Republic of Egypt, and South Africa (table 2.2). China has launched the world's largest green hydrogen facility to date but reportedly experienced significant technical difficulties during the initial start-up phase. From the top new developments recently announced, Australia, Canada, Egypt, and Mauritania each have two pipeline projects. Kazakhstan, Mozambique, and Oman announced large electrolysis projects expected to launch in the 2030s or sooner, for countries like India.[26] Additionally, Saudi Arabia's NEOM green hydrogen megaplant at Oxagon **(box 2.1, case study 1)** is due for completion by the end of 2026.

Some private sector entities across various industries are forming cross-sectoral partnerships to drive down cost curves and achieve economies of scale. Clustering users geographically offers various advantages to the industry in stimulating the demand for green hydrogen. First, leveraging the diverse applications of green hydrogen along the entire value chain enables producers to achieve economies of scale, resulting in a larger, more stable and long-term source of demand. Second, these hydrogen valleys and hubs also foster collaborative innovation,[27] allowing for shared knowledge and resources. Third, colocation reduces the need for long-haul transport infrastructure while ensuring the renewable energy origin for the hydrogen produced.[28]

Green hydrogen projects are risky for investors. They are capital intensive and are subject to evolving public policy commitments. Investors can use two contractual arrangements to boost the degree of certainty that demand exists. First, medium- to long-term offtake agreements help mitigate market risks. These agreements provide a hedge on energy prices while advancing energy transition and carbon abatement goals. Second, private-public arrangements mitigate regulatory and technology risks. For example, contracts for difference secure guaranteed payments of green hydrogen's cost gap from governments to private operators. Such contracts provide price certainty for investors. Taken together, uncertainty as to when investments in green hydrogen could become economically viable remains an obstacle for investors and policy makers considering deploying financial instruments. This highlights the importance of concessional financial resources to incentivize investment in costly, front-loaded projects, among other risks, to produce green hydrogen at scale and cheaply.

The path to mature green hydrogen markets also relies on the development and adoption of global standards. Standards are critical to quantify the carbon footprint and sustainability impact of green hydrogen and its derivatives. This requires an independent assessment of green hydrogen production, conversion, transportation, and consumption. While some voluntary national systems (such as guarantees of origin) exist for emissions certification, a global standard has yet to be established. A standardized emissions accounting framework can provide producers and consumers a common basis for meeting regulatory requirements, enhancing investment and regulatory compatibility through transparent emissions reporting. However, green hydrogen standards also influence the technologies that will dominate future markets, rewarding early adopters and creating geopolitical competition for leadership in setting these standards. Because green hydrogen standards currently vary in defining sustainability and establishing emission-counting boundaries along the supply chain, international cooperation is crucial. Consistency in data, terminology, and interpretation, as well as transparent conversion between certification programs, will be key to promoting transparency, transferability, and industry demand for green hydrogen.

BOX 2.1

Case Study 1

NEOM Green Hydrogen Project Production Cost

Saudi Arabia

The NEOM Green Hydrogen Project is the first of its kind internationally, aiming to develop one of the world's largest green hydrogen facilities. Located in the futuristic city of Neom, Saudi Arabia, this project leverages the region's abundant solar and wind resources to produce green hydrogen on a massive scale.

Key facts

- Location: Neom, Saudi Arabia
- Developers: ACWA Power Co. (33.34 percent), Air Products Qudra (33.33 percent), and NEOM (33.33 percent)
- Production capacity: 4 gigawatts of wind, solar, and battery storage
- Annual hydrogen production: 200,000 tons of green hydrogen or more than 1.2 million metric tons of green ammonia per year
- Technology: 2.2 gigawatts of alkaline electrolyzers by Thyssenkrupp Nucera and Haldor Topsoe, for the green ammonia technology and Baker Hughes for the hydrogen compression technology
- Energy sources: solar and wind power.
- Contractors: Air Products as the engineering,

procurement, and construction (EPC) contractor and system integrator, Larsen & Toubro as the EPC contractor for the power grid and power generation scope, and Envision Energy to supply the wind turbines

- Offtake: exclusive 30-year green ammonia offtake contract with Air Products and Chemicals Inc.
- Expected commercial operations date: 2026

Cost breakdown

All categories and costs are approximate, based on public sources, for illustration purposes.

Capital expenditure (CAPEX)

Total project cost: $5 billion initial, adjusted to $8.4 billion in 2023.[a]

1. Electrolyzers: investment in alkaline electrolyzers, essential for converting water into hydrogen using renewable energy.
2. Renewable energy infrastructure: construction and installation of solar panels and wind turbines to generate electricity for the electrolysis process. The contract covers the construction of a 2.2-gigawatt photovoltaic (PV) solar power generation plant, a 1.65-gigawatt wind power farm, and a 400-megawatt-hour battery energy storage system, as well as an overhead-power 306-kilovolt transmission network of 306 kilometers.
3. Hydrogen storage and transport infrastructure: development of storage facilities and logistics for hydrogen distribution.
4. Site development and infrastructure: land acquisition, construction of facilities, and necessary infrastructure, including buying spare parts up-front. The project will be paying up-front for land rights instead of leasing for 50 years.

Operating expenditure (OPEX)

Total OPEX: $120 million/year.

1. Electricity costs: cost of renewable electricity from solar and wind farms for electrolysis.
2. Maintenance and repairs: maintenance of electrolyzers, solar panels, wind turbines, Haber-Bosch ammonia plant, and other equipment.
3. Water supply: costs for sourcing, purifying, and recycling water used in electrolysis.
4. Labor costs: salaries and wages for the workforce.
5. Insurance and safety compliance: insurance premiums and regulatory compliance costs.
6. Miscellaneous operational costs: administrative expenses, utility bills, and other operational costs.

Economic and environmental impact

- Total project life-cycle OPEX-to-CAPEX cost ratio: 29 percent over 20 years (reduced after CAPEX revisions).
- Environmental benefits: the project aims to avoid close to 4 million tons of carbon emissions per year.
- Economic benefits: job creation in construction, operation, and maintenance and positioning Saudi Arabia as a leader in green hydrogen production.

Strategic significance

The NEOM Green Hydrogen Project exemplifies the feasibility and economic viability of large-scale green hydrogen production in emerging markets. By harnessing Saudi Arabia's renewable energy potential, the project aligns with global sustainability goals and sets a precedent for future green hydrogen initiatives.

Sources: Neom, "Neom Green Hydrogen Company Completes Financial Close at a Total Investment Value of USD 8.4 billion in the World's Largest Carbon-Free Green Hydrogen Plant," May 22, 2023, https://www.neom.com/en-us/newsroom/neom-green-hydrogen-investment;, Julian Atchison, "NEOM Project Reaches Financial Close, 30-Year Offtake Secured," Ammonia Energy Association, May 30, 2023, https://ammoniaenergy.org/articles/neom-project-reaches-financial-close-30-year-offtake-secured; Jennifer Aguinaldo, "Neom Finalises $6.7bn Hydrogen EPC Contract," Meed, May 22, 2023, https://www.meed.com/neom-awards-67bn-hydrogen-epc-contract; S&P Global Ratings, "Neom Green Hydrogen Co. Ltd.'s Green Facilities," April 26, 2023, https://www.spglobal.com/_assets/documents/ratings/research/101576039.pdf; and Agnete Klevstrand, "Landmark 2.2GW Neom Green Hydrogen Project in Saudi Arabia Just Got 70% More Expensive, Co-developer Reveals," Hydrogen Insight, February 5, 2023, https://www.hydrogeninsight.com/production/landmark-2-2gw-neom-green-hydrogen-project-in-saudi-arabia-just-got-70-more-expensive-co-developer-reveals/2-1-1399649.

a. Higher total project costs were related to several factors: inflation; increased costs of financing; increased scope and services, EPC contracts; upfront purchase of spares and land, instead of a land lease.

3

Pillars *for* Green Hydrogen Market Growth

At first glance, assessing a green hydrogen project might seem straightforward: How much will it cost to produce green hydrogen and deliver to the offtaker? While these criteria are critical, they are difficult to pin down in the early stages of market development, particularly in the absence of guiding regulations and policies, clarity on any fiscal support, and definitions for green hydrogen and its derivatives. As a first step, it is helpful to understand where a country or region fits into the global hydrogen market on the basis of their national priorities and potential to create demand through competitive, scalable supply.

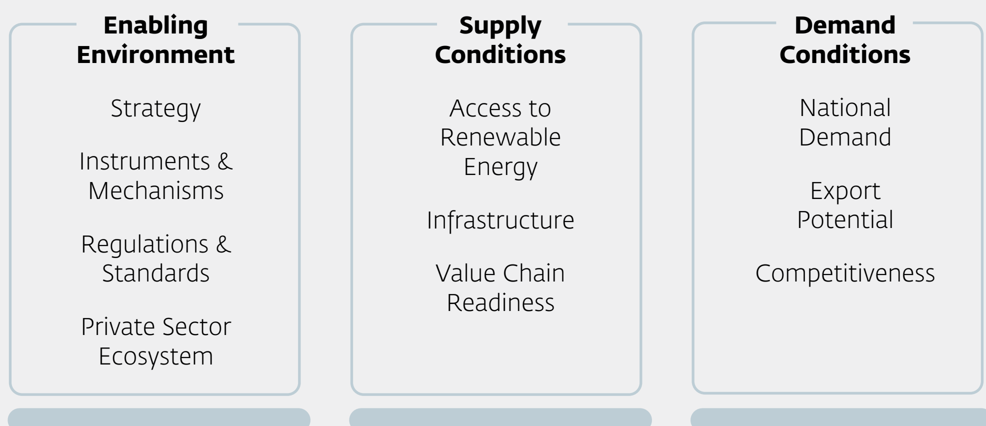
This section outlines key factors for developing a successful green hydrogen market. Each part discusses the main indicators for assessing a market's readiness for green hydrogen investments. While global examples are mentioned throughout, each section includes a detailed case study highlighting best practices from an emerging market country. The chapter is structured as follows (**figure 3.1**):

Pillar 1. Enabling environment **(box 3.1; table 3.1)** discusses how national hydrogen strategies, instruments and mechanisms, regulations and standards, and strong private sector ecosystems contribute to robust enabling environments **(box 3.3, case study 2: Chile)**.

Pillar 2. Supply conditions discusses how access to renewable energy resources, support of infrastructure, and status of value chain development contribute to creating a market with ideal supply conditions. **(box 3.8, case study 3: Brazil)**.

Pillar 3. Demand conditions discusses how domestic hydrogen demand, export potential, and global

FIGURE 3.1
Three Pillars for a Successful Green Hydrogen Project



Source: Original figure for this publication.

competitiveness contribute to creating a market with ideal demand conditions **(box 3.9, case study 4: India)**.

PILLAR 1: ENABLING ENVIRONMENT

Creating a strong enabling environment for green hydrogen deployment requires a robust combination of national policies, supporting mechanisms, and collaborative ecosystems. Strong enabling environments have four main characteristics:

- **A clear strategy** that outlines why a country will develop a green hydrogen market and that establishes clear and attainable targets to attract investors.
- **Government-backed investment mechanisms and incentives** to stimulate production (reduce costs, mitigate risks, encourage research and development, increase domestic competitiveness) and demand (attract new end users).
- **Cohesive set of regulations and standards** that establish the "rules of the game" to ensure fair competition domestically and internationally, verify impact, and provide clarity to a variety of stakeholders from production to storage and transport.
- **Active private sector ecosystem** with robust public-private partnerships and established channels for communication between policy makers and the private sector.

Importantly, there is no one-size-fits-all menu to create an enabling environment for green hydrogen, and there remains ample space for trial and error. Regardless of the approach, strong enabling environments will succeed in improving project economics, reducing risks, attracting investors, and scaling deployment. Each country will take a unique approach depending on its strengths and weaknesses within the green hydrogen value chain and how those align with its priorities across sectors.

TABLE 3.1
Elements Needed for an Enabling Environment

Established Enabling Environment	Strategy	Nationally Determined Contribution (NDC), net zero goal
		Long-term energy plan
		Hydrogen road map and/or strategy with targets
	Instruments and mechanisms	H_2 tax incentives
		H_2 subsidy programs (including contracts of difference)
		H_2 demand quotas
		RE incentives and regulatory support
		Carbon pricing
	Regulation and standards	Defining green hydrogen
		Legal framework for renewable energy
		Green hydrogen certification
		Safety and technical standards
		Regulation for production, storage, transportation, and trade
	Private sector ecosystem	Industry association, public-private initiatives and partnerships
		Existing green or low-carbon hydrogen projects (active and/or announced)

Source: Original figure for this publication.

Strategy: Why Green Hydrogen?

The foundation of a strong enabling environment is a clear national strategy that outlines a country's plan to develop a green hydrogen market. It establishes clear and attainable targets to attract investors which are complementary to other relevant strategies. The following questions can guide the definition of successful strategies:

- What is the country's agenda for a low-carbon economy?
- What are the desired impacts of green hydrogen in the clean energy transition plan?
- What are the main drivers for green hydrogen development, including economic, trade, political, innovation, collaboration, and so on? (For example, domestic industrial decarbonization, renewable energy deployment, international hydrogen trade/export participation, and so forth.)
- Is green hydrogen the best choice?
- How will the government support the development of a green hydrogen market?
- Is there existing infrastructure that can be leveraged or repurposed?
- Are there favorable conditions, geographic positioning, and access to resources that can create competitive advantages?

- What are the guiding principles for green hydrogen deployment?

The answers to these questions will vary depending on national priorities. For example, the *European Union* hopes green hydrogen can contribute to improved energy security as it faces supply challenges following the Russian invasion of Ukraine and low natural resource availability. Thanks to excellent solar and wind resources, *Latin America* and *Australia* could avail themselves of a vast export opportunity while addressing domestic issues of curtailment and intermittency. *Türkiye* intends to blend hydrogen into its natural gas pipelines. One universally shared guiding principle is to help achieve national climate goals, particularly the decarbonization of sectors for which there is no clear alternative (oil refining, chemicals, and steel). A strategy that clearly states these objectives and provides quantitative evidence supporting them (through technical assessments, feasibility studies, infrastructure planning, and so on) will attract the relevant stakeholders and capital required.

At the time of publication, 52 countries have released national hydrogen strategies, with 29 in preparation. Of the 52 national hydrogen strategies, nearly 30 are in emerging markets.[29] The majority (31) of national strategies were released between 2021 and 2022, potentially in response to the global pandemic, which threatened energy supply chains and overall economic development. Strategies range in depth from single-page briefs to detailed 100+-page reports. Many large economies focus on their domestic decarbonization needs through their own capacity building (China, France, United States). Several developed countries and nations with limited resources plan to import from others (EU, Germany, Japan, Korea, Singapore, Uzbekistan). **See box 1.**

Map 3.1 shows the map of countries with H2 strategies and **table 3.2 outlines** targets set for 20 green hydrogen strategies from emerging markets.

For emerging countries, the drivers and focus for green hydrogen program deployment vary from those of major economies. Most developing countries with cheap renewable energy sources choose the export-oriented path (Argentina, Brazil, Chile, Colombia, Egypt, India, Morocco, South Africa). This is reflected in their key drivers, such as international trade and innovation, which differ from energy security and decarbonization of the economy, motivations more typical for domestic or import-oriented objectives. However, even export-oriented countries must begin their green hydrogen journeys by setting realistic targets and building domestic capacity before embarking on the hydrogen trade. Particularly, in order to reduce a dependence on hydrogen import policy support in developed markets, emerging markets should encourage domestic demand.

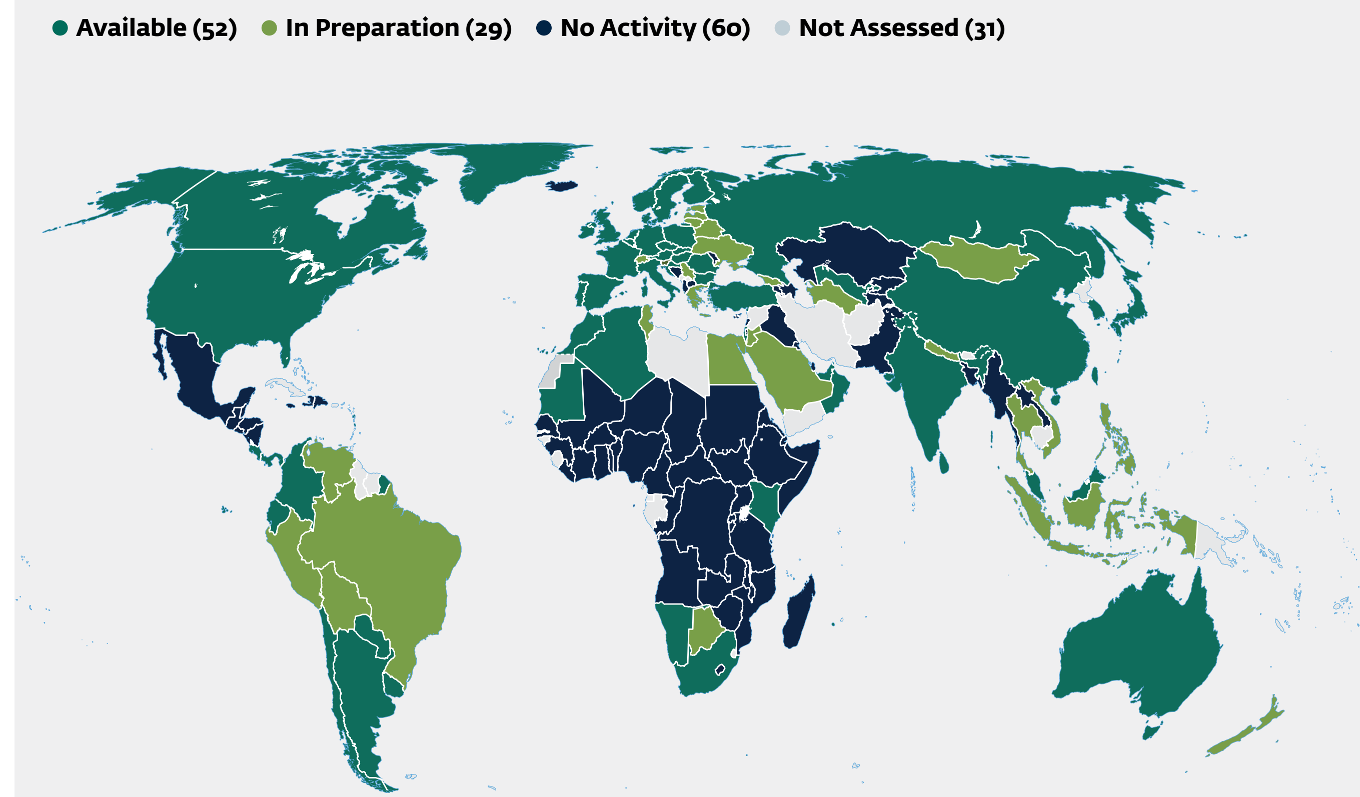
Just under half of available hydrogen strategies set specific electrolyzer targets for 2030. Chile is the most ambitious country, aiming for a 25-gigawatt electrolyzer capacity by 2030. Some nations, such as South Africa, set ranges to target capacities between 11.7 and 16.7 gigawatts by 2030. However, many omitted targets can indicate the insufficient depth of planning in the strategy process **(table 3.2)**.

In most cases, the relevant ministry covering energy affairs leads the development of the hydrogen strategy, sometimes independently but other times with support from other ministries and stakeholder groups, such as

- Relevant ministries (Ministry of Foreign Affairs, Economy and Finance, Environment, and so forth)
- State-owned companies that manage important assets such as ports, industrial parks, pipelines, and power systems
- Donor governments (Germany, the Netherlands, UK)
- Academic institutions
- Institutions for research and development

MAP 3.1

Map of Hydrogen Strategies, as of October 6, 2023



Source: BloombergNEF.

Note: Mapped data show strategies for distinct economies. A full list of strategies can be found in Global Hydrogen Strategy Tracker |, https://www.bnef.com/insights/28035/view.

TABLE 3.2

Hydrogen Strategies in Emerging Markets (Select 20 Countries)

Country	Date Released	Electrolyzer Target (GW)		Key Drivers	Domestic or Export/Import-Oriented
		2030	2050		
Brazil	2022	n.a.	n.a.	International trade, decarbonizing the economy	Export
Chile	2020	25	n.a.	Decarbonizing the economy	Domestic, import
China	2022	n.a.	n.a.	Energy security	Domestic, import
Colombia	2021	1–3	n.a.	International trade	Export
Costa Rica	2022	0.2–1	n.a.	Decarbonizing the economy	Domestic, import
India	2022	n.a.	n.a.	Energy security	Domestic, export
Kenya[a]	2023	0.15–0.25	n.a.	International trade	Export
Morocco[b]	2021	n.a.	n.a.	International trade	Export
Namibia	2022	n.a.	n.a.	International trade	Export
Oman	2022	n.a.	n.a.	International trade	Export
Panama	2023	n.a.	n.a.	International trade	Export
Paraguay	2021	n.a.	n.a.	Undetermined	Undetermined
Poland[c]	2021	2	6 (2040)	International trade	Export
Romania[d]	2023	2.1	4	Decarbonizing the economy	Domestic
South Africa	2022	11.7–16.7	n.a.	Environmental and social benefits	Domestic, export
Trinidad and Tobago	2022	n.a.	25 (2065)	International trade, decarbonizing the economy	Domestic, export
Türkiye	2023	2	70 (2053)	Decarbonizing the economy	Domestic, export
Uruguay	2022	1–2	10	International trade, innovation	Export
Uzbekistan	2021	n.a.	n.a.	Decarbonizing the economy, energy access	Import
Viet Nam	2022	n.a.	n.a.	International trade	Export

Sources: BloombergNEF, IHS, and internet searches.

Note: Includes only emerging markets. For reference, the United States has set a demand target of 50 million metric tons per year by 2050 (more than 2× the same goals of Japan and Canada) while the EU aims to produce 10 million metric tons and import 10 million metric tons per year by 2030. Assumes that 1 million metric tons per annum (mmtpa) = 33.3 terawatt-hours.

a. Electrolyzer target is 150 to 250 megawatts by 2032; aims for 20 percent substitution (100,000 tons/year) of nitrogen fertilizer by 2027 and 100 percent substitution (>5,000 tons/year) of methanol by 2027; then 50 percent substitution (200,000 to 400,000 tons/year) nitrogen fertilizer by 2032.

b. Domestic demand for green hydrogen and its derivatives could grow to 4 terawatt-hours by 2030 and 22 terawatt-hours by 2040. An additional 10 terawatt-hours of hydrogen could be exported by 2030, with this number increasing to 46 in 2040 and 115 terawatt-hours in 2050.

c. Poland is the third biggest hydrogen producer in Europe and the fifth in the world, with an annual production volume of around 1.3 million metric tons (of gray and blue H_2).

d. Targets production of 0.137 million metric tons of green hydrogen and 0.003 million metric tons of low-carbon hydrogen by 2027. By 2030, targets 0.282 million metric tons of green hydrogen and 0.007 million metric tons of low-carbon H_2.

- National laboratories
- International development organizations (World Bank, Inter-American Development Bank, United Nations, Deutsche Gesellschaft für Internationale Zusammenarbeit, Green Climate Fund)
- Independent consultants (McKinsey, Boston Consulting Group)
- Nongovernmental organizations (Rocky Mountain Institute)
- Private sector companies
- Industry associations

In the absence of a specific green hydrogen national strategy, a country can also communicate its hydrogen ambitions in several ways: through its nationally determined contribution, long-term energy plan, industrial decarbonization strategy, infrastructure plan, strategy for carbon neutrality (Cambodia,[30] Indonesia[31]), or other policy document. Some 26 emerging-market countries are actively preparing national strategies. In the interim, they are releasing statements that they are conducting independent or cosponsored assessments, frameworks, or road maps (Ecuador,[32] Egypt,[33] Jordan,[34] Peru,[35] the Philippines,[36] Tunisia,[37] Turkmenistan[38]); have formed committees or mandated specific groups to develop strategies (Algeria[39]); or have released requests for support from international organizations (Thailand[40]).

Instruments and mechanisms: Tax incentives, subsidy programs, demand quotas, renewable energy incentives, and carbon pricing.

Access to finance, high up-front capital expenditures, and lack of long-term offtake contracts remain some of the biggest obstacles to deployment, but government-backed investment mechanisms and incentives can help reduce costs, mitigate real or perceived risks, encourage research and development

BOX 3.1

US and EU National Clean Hydrogen Strategies and Incentives

As of publication, the United States and the European Union have the most robust national green hydrogen strategies.

United States: The US National Clean Hydrogen Strategy is a comprehensive framework to accelerate the production, processing, delivery, storage, and use of clean hydrogen. It outlines three priorities (demand, production, and regional hubs) for deploying $9.5 billion grants over four years, with the near-term goals of producing 10 million metric tons of hydrogen per year by 2030, reducing the cost of clean hydrogen to $1 per kilogram by 2031 and ramping up scale through deployment of regional clean hydrogen hubs. The US Inflation Reduction Act also promises up to $3 of tax credit over 10 years per kilogram of clean hydrogen produced. At the time of writing this report, the US Treasury's guidelines for calculating life cycle emissions to access the hydrogen production tax credits have yet to be published.

European Union: Building off the European Green Deal (2019) and Renewable Energy Directive II (established 2016, legally binding as of 2021), the EU Hydrogen Strategy (2020) and the REPowerEU (2022) plan to provide comprehensive frameworks to (among other goals) support the production and consumption of green hydrogen[a] in the EU. Notably, two delegated acts[b] were adopted in 2023 to define the conditions under which the EU considers hydrogen "renewable" so as to align with REPowerEU and Fit for 55.

a. The REPowerEU Strategy of 2022 targets producing and importing 10 million metric tons of green hydrogen by 2030. By 2050, it aims for green hydrogen to meet 10 percent of the EU's energy needs, significantly decarbonizing industries and transport.

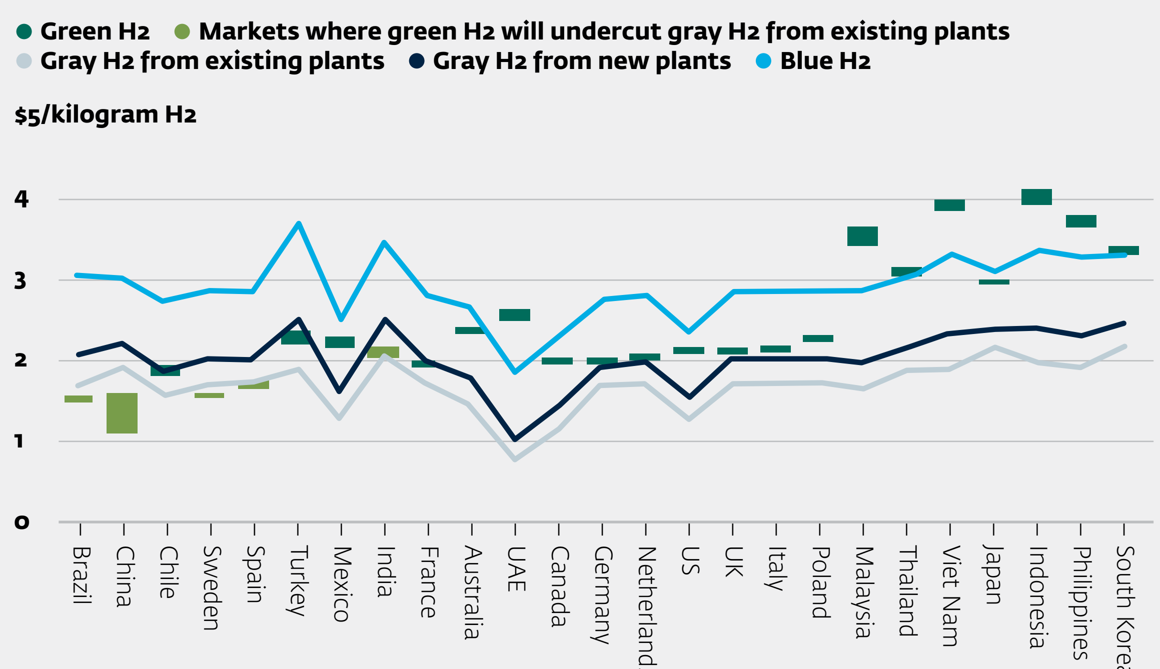
b. (a) The renewable hydrogen definition and production criteria; and (b) greenhouse gas emission savings methodology.

(R&D), scale up production, and attract demand. High financing costs are influenced by high renewable energy production costs and electrolyzer costs (and additional bankability risks outlined in pillar 2), which, to compete with fossil fuel–derived hydrogen, should be at or below $1.60 per kilogram. Production costs are notoriously difficult to predict and are location specific. **Figure 3.2** provides estimated costs for projects in 2030 for different types of hydrogen.

Globally, $360 billion worth of subsidies are available to support green hydrogen supply and demand. Nearly 90 percent of these programs in total dollar volume are in North America (the United States and Canada), the European Union (Germany and the Netherlands), and Japan—all of which are major demand centers **(table 3.3)**. The first emerging-market countries with subsidy programs for green hydrogen and its derivatives are China ($5 billion) and India ($2 billion), both focused on green hydrogen supply. On a smaller scale, Egypt passed a new green hydrogen incentives law in January 2024, giving tax credits of 33 to 55 percent and other exemptions. The Chilean government pledged $50 million in grants to six green hydrogen projects and is creating a $1 billion fund to catalyze private investment.

Most subsidies support supply-side projects ($171 billion, or 61 percent of total global green hydrogen government subsidies), while $93 billion is used for both supply and demand projects and $17 billion is used for demand-side projects only. Most of the government subsidies are available to projects in the United States, Canada, or the European Union. Funding for supply-side projects outside these locations amounts to just over $20 billion. Within emerging markets, India's National Green Hydrogen Mission provides the most supply-side support, totaling $1.59 billion for green hydrogen production to be paid out over three years[41]. Although a leader in emerging markets, India's subsidies for the per-kilogram production of green hydrogen ($0.61 in year 1, $0.49 in year 2, and $0.37 in year 3, which are ceiling prices for competitive auctions) fall far below the United States' maximum allowance of $3 per kilogram over 10 years.

FIGURE 3.2
Global Hydrogen Production Costs (2030)



Source: BloombergNEF.

Note: Blue H2 is the average of auto-thermal reforming (ATR) and steam methane reforming (SMR) production. Green H2 includes Western-made proton-exchange membrane electrolyzers (top of range) and alkaline electrolyzers (bottom of range), except in China, which includes Chinese-made alkaline electrolyzers (bottom of range).

Establishing the rules of the game: Regulations, definitions, certification programs, and safety and technical standards.

Countries also need to consider how green hydrogen fits into already existing (or planned) enabling environments for renewable energy. Many emerging market countries have recently adopted new policies to minimize the disruption to electricity access, quality, and affordability through their COVID-19 recovery packages.[42] According to the World Bank,[43] since 2020 more than 80 percent of countries surveyed globally have improved their regulatory environments for sustainable energy. Examples of regulatory support for renewable energy include the following:[44]

TABLE 3.3
Global Hydrogen Subsidy Amounts and Select Examples by Mechanisms

Mechanism	Total amount available (billions of $)	Examples
Contract for Difference	7.60	Germany: H2Global
		Japan: Nesahoten
		United Kingdom: Hydrogen Production Business Model
Fixed Premium	10.44	Netherlands: Stimulation of Sustainable Energy Transition auction program (SDE++)
		India: National Green Hydrogen Mission
Grant Program	102.62	European Union: IPCEI
		United States: regional clean hydrogen hubs
Research and Development Funding	18.39	United Kingdom: Industrial Energy Transformation Fund
		Japan: Green Innovation Fund
Tax Credit	141.26	United States: 45V hydrogen production tax credit
		Canada: investment tax credit for clean hydrogen

Source: Original figure for this publication.

- *Legal framework for renewable energy:* allowance for private sector ownership of renewable energy generation, official and legally binding renewable energy targets linked to international commitments such as the Nationally Determined Contributions (NDCs), and the existence of a renewable energy action plan or strategy.
- *Planning for renewable energy expansion:* assessments, targets, reporting mechanisms, clear guidelines, and institutional support/ownership for renewable energy expansion in specific sectors and within generation and transmission planning.
- *Incentives and regulatory support for renewable energy:* specific support for electricity (for instance, long-term power purchase agreements, feed-in tariffs, competitive auctions, energy banking, subsidies, grants, and tax incentives); electrified transport, heating, and cooling; prioritized access to the grid and in dispatch; and mechanisms to support projects for delayed infrastructure and curtailment.
- *Network connection and use:* grid code and rules with clear connection procedures that address variable renewable energy, specifically the ability to sell into balancing/ancillary services.
- *Counterparty risk:* creditworthiness, payment risk mitigation, and utility transparency and monitoring.
- *Carbon pricing and monitoring:* carbon costs can affect energy affordability or improve the relative price of renewables compared with fossil fuel alternatives.

A cohesive set of regulations and standards that establish the rules of the game can ensure fair competition domestically and internationally, verify impact, and provide clarity to a variety of stakeholders from production to storage and transport. Whereas strategies outline a country's ambitions for green hydrogen, the rules of the game should clarify what constitutes green hydrogen (or blue, low carbon, renewable, and so on) and allow for consumer transparency, price segmentation, and the tracing of hydrogen contributions toward decarbonization goals. When clearly outlined and communicated, these tools reduce risks to project developers, technology suppliers, lenders, and investors, building confidence among all stakeholders. Governments, international organizations, corporations, industry associations, and nongovernmental organizations have a role to play in this process. For this report, we use the following terms:

- *Definitions* outline the parameters and limits for how a product is categorized or labeled (for example, "renewable," "green," and/or "low carbon") on the basis of concepts such as additionality, temporality, geography, emissions intensity, and final product.
- *Certification programs* are the mechanisms by which a product is verified according to certain standards, which should theoretically align with definitions.
- *Frameworks* are the policy guidelines that indicate a country's or region's position related to definitions.
- *Regulations* are the legal tools used to implement the framework.

At the time of publication, there is not a globally recognized, accepted, or regulated green hydrogen definition and certification program.[45] However, there are several early movers. The European Union has already legally defined and set frameworks for the regulation of green hydrogen production and imports. The United States released its first Clean Hydrogen Guidance for domestic producers at the end of 2023. At the COP28 climate summit in December 2023, 36 countries, including Australia, Brazil, Canada, EU nations, India, South Africa, and the United States, committed to mutual recognition of clean hydrogen certificates that would facilitate international trade of clean hydrogen for the first time.[46] Each country will need to develop a clear strategy before establishing definitions and regulations that support their needs. However, ensuring consistency (particularly when defining what qualifies as green hydrogen) will be essential to generating a global marketplace.

TABLE 3.4

Types of Mandatory EU Regulations for Green Hydrogen Production

Type of Requirement	Reason	Challenges	Regulation (example: European Commission Renewable Energy Directive II [RED II])
Overall emissions thresholds: how many emissions are released over a certain period as a result of green hydrogen production	Green hydrogen must have significantly reduced emissions compared to alternative to be used as a valid decarbonization tool.	Variation in the type of emissions counted, life cycle boundaries, measuring standard used, and measuring technology readiness and variation across emission pricing systems	Maximum 3.38 kg of CO_2e[a]/kg of H_2 from upstream methane emissions to point of use.[b]
Additionality: whether the electrolyzer is powered by a renewable energy resource that is new or built within a certain timeline	To ensure that new electrolyzer capacity is not taking clean electrons away from other (potentially greater climate impact) uses	Potential for significant variation between the time required to access new renewable electricity generation assets (either grid connected or otherwise) compared with (a) the urgency to produce green hydrogen and (b) the time required to set up an electrolyzer	Starting in 2028, allow a maximum of 36 months (3 years) between first operation of renewables and hydrogen production. Hydrogen production capacity entering operation before 2028 is exempt until 2038.[c]
Temporal correlation: hydrogen is produced when renewable energy is available.	To ensure that additional demand for renewable sources powering green hydrogen production does not incentivize more fossil fuel electricity generation elsewhere	Hourly matching limits electrolyzers utilization rate, thus increasing production costs	Monthly matching is permitted, switching to hourly matching in 2027.[d]
Geographic correlation: hydrogen is produced where renewable energy is available.	Same as for temporal plus to ensure that grid-connected electrolyzers do not dominate limited interconnector capacity	Compliance across different types of electricity markets	Grid electricity must be bought in the same power market bidding zone as the electrolyzer; neighboring bidding zones allowed when market prices ≥ local bidding zone.[e]

Source: World Bank.

a. CO_2e = carbon dioxide equivalent; H_2 = hydrogen.

b. European Commission, "Renewable Hydrogen," 2023, https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen-delegated-acts_en.

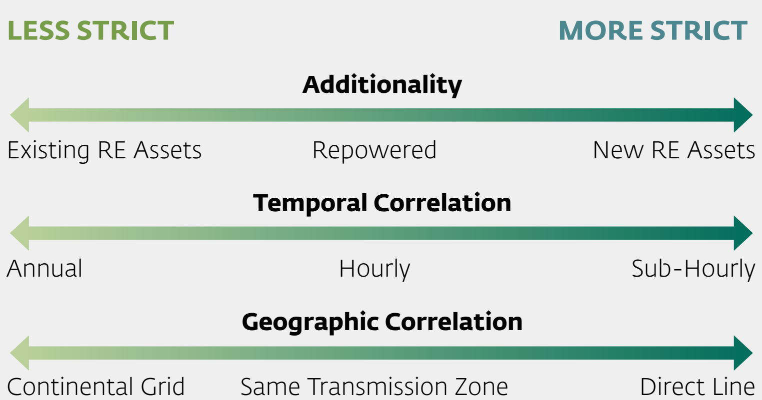
c. European Commission, "Renewable Hydrogen."

d. European Commission, "Renewable Hydrogen."

e. European Commission, "Renewable Hydrogen."

FIGURE 3.3

Comparing Regulatory Strictness



Source: Original figure for this publication.

The green hydrogen regulatory debate is based largely on three main concepts: emissions intensities and the location and timing of renewable energy production. **Table 3.4** provides a comprehensive explanation of each concept, major challenges, and how leading stakeholders, such as the European Union, are addressing them. **Figure 3.3** offers a comparison of stringencies of various options. Understanding the distinction between labeling and measuring is crucial: numerical measurement should be the preferred method, since labels like "clean" can be misleading. Emissions intensities can vary significantly depending on how they are defined, measured, and certified, underscoring the need for a rigorous approach.

Green hydrogen definitions and standards should also seek to standardize emissions tracking and verification methodology, be flexible enough to work for different products (for example, ammonia versus methanol), and consider market barriers across borders. To truly scale adoption, a transparent, low-cost, and easy-to-follow certification system must be stated and aligned with global and national policies and end-user needs. **Table 3.5** provides information on a selection of leading voluntary certification systems that are active or in development around the world.

Finally, the physical properties of hydrogen (and its derivatives) require specific regulatory and safety standards to avoid harm to the workforce, infrastructure, and the broader environment. Clearly established safety requirements must account for expected growth in the sheer quantity of products on the market and their use in new applications. Although hydrogen has been used in industry for many decades, its emerging applications in consumer environments (such as transport, buildings, and long-duration energy storage) require new associated codes and standards that are at various stages of development.[47] In standard conditions (0°C and 1 atmosphere of pressure), hydrogen occurs as a colorless, odorless, tasteless, nontoxic, and highly combustible gas, making it hard to detect.[48] In this form, it shares many of the safety concerns for natural gas: it is highly flammable, and when not properly stored and transported, leakage can lead to explosions. However, because of its low density, high flame temperature, and wide ignition range, hydrogen, when leaked, burns more readily than natural gas.[49]

Whether stored or transported as gas or liquid or converted into ammonia, clear safety and technical regulations must be in place to avoid accidents and physical harm to infrastructure and the people who manage it. Thanks to more than 80 years of industrial use of hydrogen, such standards already exist.[50] Types of safety standards include the following:

- *Leakage or discharge control:* ventilation (passive/natural or active) to prevent accumulation if a leak or discharge occurs

TABLE 3.5

Selected Voluntary Certification Programs

Program	Description	Definitions	Alignment
EU CertifHy	An industry-led market-based voluntary mechanism developed at request of European Commission in 2014, financed by Clean Hydrogen Partnership. Focused on consumer disclosure	Must have ≤60% emissions compared with those of fossil fuel–derived hydrogen **Green:** ≤4.0 g of CO_2ea/g of H_2 inclusive of upstream methane to the point of production + GO + additionality + renewable powered electrolysis or biogas SMR **Low carbon:** ≤4.0 g of CO_2e/g of H_2 inclusive of upstream methane to the point of production + GO + nuclear- or grid-powered electrolysis or fossil SMR/ATR with carbon capture	Renewable Energy Directive II (RED II) established a mandate to require the adoption of national guarantee of origin systems for hydrogen in each member state. Several EU member countries are designating CertifHy as their issuing body, although some EU countries may choose to have their own systems.
TÜV SÜD *CMS 70*	Developed in 2011 with a focus on Germany. Differentiates by end use (transport or other).	**Green for transport:** ≤2.7 g of CO_2e/g of H_2 inclusive of upstream methane to point of use + GO + additionality + renewable-powered electrolysis or biogas SMR **Green for other uses:** ≤2.8 g of CO_2e/g of H_2 inclusive of upstream methane to point of production + GO + additionality + renewable-powered electrolysis or biogas SMR	Applies CertifHy thresholds for emissions and is aligned with REDII and its delegated acts
GH2 Green Hydrogen Standard	A voluntary industry standard developed by the Green Hydrogen Organization and launched in May 2022, with the most stringent requirements on the market.	**Green:** ≤1.0 g of CO_2e/g of H_2 inclusive of upstream methane to the point of production + GO + renewable-powered electrolysis	Builds on the emissions calculation methodology proposed by the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE). IPHE is an intergovernmental organization working toward harmonizing the carbon intensity definitions of various different types of hydrogen.

Source: World Bank.

Note: ATR = autothermal reforming; GO = guarantees of origin; H_2 = hydrogen; SMR = steam methane reforming.
CO_2e = carbon dioxide equivalent.

- *Leakage detection:* hydrogen/flammable gas detectors, consistent monitoring of internal piping pressures and/or flow rates, portable flame detectors (thermal imaging camera)
- *Flame detection:* thermal and optical sensors that provide a rapid and reliable flame indication, automatically shut off or isolate the source, shut down the system to safe mode, control active ventilation, and activate audible and visual alarms
- *Electrical equipment management:* ideally nonsparking and electrically bonded/grounded
- *Emergency shutdown system:* located on and near equipment and activated by alarms, loss of ventilation, or manual devices
- *Storage:* based on quantity of hydrogen, store at safe distance from structures, ventilation intakes, and vehicle routes. For bulk (>5,000 standard cubic feet) hydrogen compressed gas systems, include pressure regulators and relief devices, compressors, manifolds, and piping.
- *Materials:* preferably stainless steel, aluminum alloys, copper, and copper alloys. Avoid nickel (subject to embrittlement) and cast iron.

The list is not exhaustive. Extensive additional safety and technical standards depend on the scale of production and the value chain segment (production, transport, storage, use), with further detail required within each component (for example, hydrogen production from offshore wind will initiate different types of siting requirements than solar; transporting liquid hydrogen in pipes will have technical and regulatory requirements very different from those for transporting ammonia in trucks; blending hydrogen into existing gas pipelines will require additional regulations, and so on).[51] Countries can anticipate these challenges (and associated costs) by developing comprehensive national hydrogen strategies that clearly define their intentions, assess the suitability of existing infrastructure (such as ammonia storage and natural gas pipelines), and generally lay the groundwork for evolving more specific regulations and standards.

As the amount of hydrogen produced and used globally grows, accidental consequences of poor safety standards could be a risk. Emerging-market actors must participate early and often in cross-border learning with experienced players. **Table 3.6 provides** examples of international groups working on hydrogen safety issues.

TABLE 3.6

Examples of International Cooperation for Hydrogen Safety

Initiative	Activities	Example Members
Center for Hydrogen Safety (part of AIChE)	• CHS conference • Codes and Standards Database • Hydrogen Safety Panel • CHS Fundamental Hydrogen Safety Credential • Introduction to Hydrogen Safety for First Responders • H2Tools Portal (hosted by PNNL) • Courses and webinars	Air Liquide, Air Products, Bayotech, Bloom Energy, BP, CF Industries, Chevron, Cummins, Electric Hydrogen, ENGIE, Equinor, Linde, Plug Power, Shell
International Association for Hydrogen Safety (hySafe)	• International Conference on Hydrogen Safety • Biennial Report on Hydrogen Safety • Research Priorities Workshops	Air Liquide, Equinor, Fraunhofer, Shell, Kawasaki Heavy Industries

Source: World Bank.

Note: AIChE, American Institute of Chemical Engineers; CHS = Center for Hydrogen Safety; PNNL = Pacific Northwest National Laboratory.

TABLE 3.7

Select Companies Active in Emerging Markets

Type	Companies
Electrolyzer and Fuel Cell Manufacturers	Cummins Hydrogenics, ITM Power, HydrogenPro, Plug Power, John Cockerill, Linde, McPhy, Nel, ThyssenKrupp, Sunfire, Siemens, Peric, Longi
Industrial Gas Companies	Air Liquide, Air Products, Uniper, Enagas, Unigel
Energy Utilities/Oil and Gas Companies	Acme Group, Iberdrola, Acciona, ACWA Power, BP, ENGIE, Scatec, Chariot, CWP Global, EDF Energy, Enel, Enertrag, ReNew, Shell, TotalEnergies, RWE AG
Chemical Companies	Yara International, Jindal, Sasol, Enaex, OCP Group, Fertiglobe
EPC Companies	Black & Veatch, Larsen & Toubro, Fluor
Investors	Actis LLP, Copenhagen Infrastructure Partners, Hy24, GIC, Canada Pension Plan
Other (port authorities, mining operations, fertilizer producers, explosive producers, new/clean energy producers, and so on)	Amsterdam Port Authority, Antwerp Port Authority, ArcelorMittal, Maersk, Anglo American, Fortescue Future Industries

Source: Original table for this publication.

Note: EDF = Electricite de France SA; GIC = Government of Singapore Investment Corporation; RWE AG = Rheinisch-Westfälisches Elektrizitätswerk.

Private sector ecosystem

The global ambitions of green hydrogen development can be achieved only with a robust public-private de-risking ecosystem, collaboration between policy makers and the private sector, and a solid pipeline of existing and future projects. In emerging markets, the private sector has often demonstrated stronger action than the public sector. Many of the world's top energy, chemicals, and EPC companies have substantial experience working with hydrogen, whether through established hydrogen initiatives within their corporate structure, memberships in an industry association, or announced partnerships and joint ventures. Most of these companies are active in emerging markets, including but not limited to Iberdrola, BP, Enel, ENGIE, ArcelorMittal, EDF Energy, Fertiglobe, AES, Yara, OCP, Shell, Sasol, and Total **(table 3.7)**.

The industry boasts a diverse international community consisting of global and national hydrogen industry associations, private sector members, research institutions, and international governmental and nongovernmental organizations. The World Hydrogen Council, representing a global initiative of more than 100 private sector companies engaged in the hydrogen business, is the most recognizable association. Additionally, there are many national- and regional-level initiatives focused on developing local hydrogen economies. The World Bank has recently launched two notable initiatives to advance green hydrogen in emerging markets: Hydrogen for Development Partnership (H4D) **(box 3.2)**, which brings together many industry groups and stakeholders, and the 10 GW Clean Hydrogen Initiative to stimulate new project development.

Key success factors for establishing the rules of the game:

- Set realistic regulatory guidelines that enable market development and deliver decarbonization impact.
- Ensure alignment across national borders at the global level to support fair competition, validate impact, and provide clarity to stakeholders across the value chain.
- Design flexible green hydrogen standards to support interoperability across a wide range of jurisdictions, products and applications.
- Participate in global communities of practice to share lessons learned and best practices across the public and private sectors.

BOX 3.2:

The Hydrogen for Development Partnership (H4D)

Launched at COP27 in 2022, the World Bank Group's Hydrogen for Development Partnership (H4D) initiative will help catalyze financing for hydrogen investments from both public and private sources. By bringing together hydrogen stakeholders and channeling synergies, the partnership focuses on capacity-building and regulatory solutions, business models, and technologies to support the roll out of green and low-carbon hydrogen in developing countries.

H4D is based on three pillars, as seen in **table B3.2.1**.

TABLE B3.2.1

Three Pillars of H4D

GLOBAL KNOWLEDGE	TECHNICAL ASSISTANCE	FINANCING
• Green Hydrogen reports with **viable opportunities.** – Report on green Hydrogen in Developing Countries. • Development of **guarantees of origin.** – Support Chile, Colombia, and India to comply with international standards. • Access to **international and regional platforms.** – Mission Innovation and H2LAC.	• Development **Strategies** and **Roadmaps** nationally and regionally. – India, Morocco, Oman, Qatar, Saudi Arabia, UAE. • **Policies, regulations, and standards** to boost offer and demand. – Brazil, Mauritania, Morocco, Tunisia, and Uzbekistan. • **Capacity building** to develop hydrogen projects. – Chile, Colombia, Costa Rica, India, and Namibia.	• Concessional financing for **large scale projects, through IFC.** – Barbados, Mexico, and South Africa. • Concessional finance for **governments.** – Chile, India, and Namibia. • Mobilize **climate funds** and other concessional resources.. – CIF, GCF, GEF, SDG partnership, and SFLAC.

As of publication, H4D counted 42 members, as seen in **figure B3.2.1**.

FIGURE B3.2.1

Members of H4D

For more information or to join H4D, visit ESMAP https://www.esmap.org/Hydrogen_for_Development_Partnership_H4D

BOX 3.3
Case Study 2

Chile's Green Hydrogen Strategy

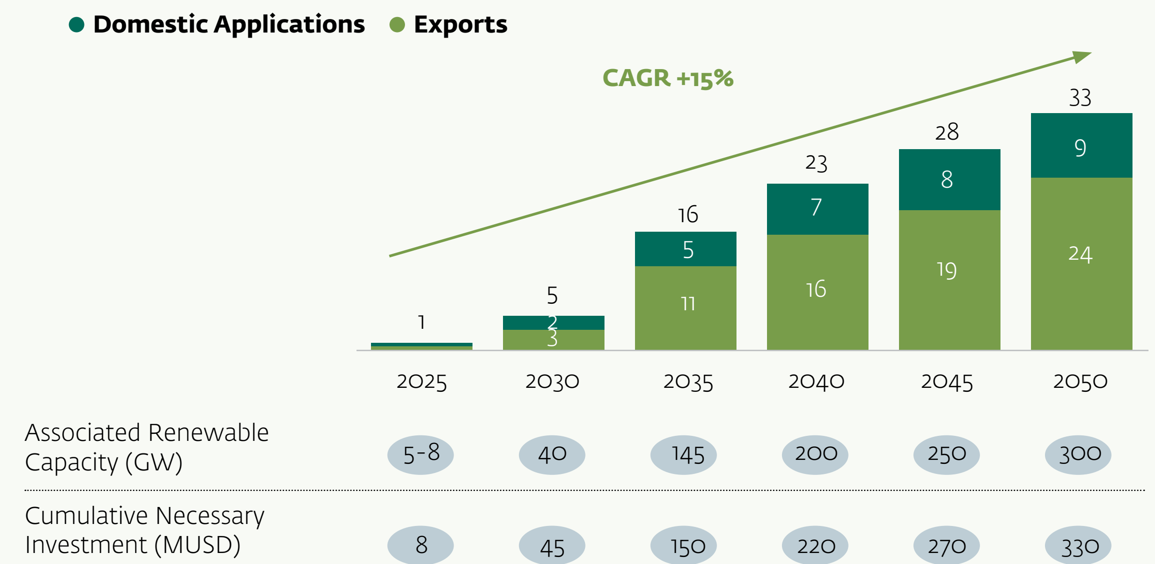
Chile has the most ambitious green hydrogen agenda in the Latin America and Caribbean region. Aiming to produce the cheapest green hydrogen on the planet by 2030, the country is focused on becoming a global green hydrogen export powerhouse **(table B3.3.1)**.

TABLE B3.3.1
Key Statistics: Chile

Hydrogen Strategy	Chile's National Green Hydrogen Strategy published in 2020 by the Ministry of Energy with support from McKinsey & Company.			
Energy Mix (2022)		INSTALLED	UNTAPPED	
	Wind	4.3 GW	76.7 GW	
	Solar PV	6.14 GW	2079.86 GW	
	Hydro	7.29 GW	2.71 GW	
Existing Electrolysis Projects	ANNOUNCED	FINANCED	OPERATIONAL	
	23	0	1	
Top 5 Hydrogen Projects by Volume	COMPANY	PROJECT NAME(S)	ESTIMATED HYDROGEN OUTPUT (metric tons/year)	INTENDED USE
	TotalEnergies SE	Total Eren Magallanes	800,000	Ammonia export
	Verano Energy SPA Siemens AG	Los Amigos del Verano	400,000	Ammonia export
	Albatros Investments Consulting Group	Albatros Selknam	282,200	Ammonia export
	TEG UK Ltd	Gente Grande	228,000	Ammonia export
	CWP Global	CWP Global Magallanes	170,000	

Sources: The Chilean Ministry of Energy, BloombergNEF, and Hinicio.

FIGURE B3.3.1
Chile Green Hydrogen Projections (2025–50)



Source: Government of Chile, "National Green Hydrogen Strategy," Ministry of Energy, November 2020, 12, https://energia.gob.cl/sites/default/files/national_green_hydrogen_strategy_-_chile.pdf.

Strategy

The foundation of Chile's green hydrogen market is an ambitious national green hydrogen strategy with set targets for 2025, 2030, and 2050. The National Green Hydrogen Strategy was the first of its kind in emerging markets and currently aims for the highest electrolysis deployment globally at 25 gigawatts electrolysis by 2030 (able to produce up to 2.8 Mt hydrogen[a]), with an ambition to develop the world's leading markets for both domestic applications and exports **(figure B3.1.1)**.

Chile will leverage green hydrogen production to help meet its Nationally Determined Contribution goals — aiming for green hydrogen to help reduce 21 percent of total greenhouse gas emissions by 2050 (71 percent in cargo transport, 12 percent in industry and mining motor use, seven percent in housing and two percent in industry).[b]

Chile has set specific sales targets (demand) for the following industries (2050):[c]

- Oil refineries: $0.2 billion
- Ammonia: $0.5 billion
- Mining trucks: $1.6 billion
- Heavy duty tracking: $2.0 billion
- Long range buses: $0.8 billion
- Blending into gas grid: $0.3 billion

Chile's hydrogen production ambitions may face challenges securing offtake. If the projected 25 gigawatt production capacity is achieved by 2030, hydrogen importers will need to significantly increase their demand. On a positive note, Chile's National Green Hydrogen Strategy answers nearly all the key questions identified in **table B3.3.2**.

TABLE B3.3.2
Questions

What is the country's agenda for a low carbon economy?	Commitment to reducing greenhouse gas emissions to help slow down global climate change, moving towards sustainable development. Low cost, abundant clean energies will decarbonize the country's activities, diversify its energy matrix, and generate new industries for local development. Transition from the economy of nonrenewable resources to one that produces clean, sustainable fuels.
What are the desired impacts of the green hydrogen economy?	• Domestic growth and development opportunity, including the creation of up to 100,000 new jobs. • Move Chilean economy away from dependence on extractives. • Help other markets decarbonize affordably and dependably. • Decarbonize domestic industry (maritime, transport, mining, industry, and power).
What are the main drivers for green hydrogen development including economic, trade, political, innovation, collaboration?	• Decarbonize the economy to reach net zero emissions by 2050.[a] • Develop green hydrogen domestic and export markets. • Achieve environmental and social co-benefits.
Is green hydrogen the best solution compared to alternatives?	The strategy does not explicitly discuss how green hydrogen will be used alongside alternative or complementary decarbonization technologies, although it does suggest that multiple technologies will be necessary.
How will the government support the development of a green hydrogen market?	• Government funding of $50 million • Establishment of public-private roundtable • Deployment of a green hydrogen diplomacy • Establishment of a regulatory development plan • Establishment of a permitting and piloting task force • Introduction of green hydrogen quotas • Creation of mechanisms to support community engagement • Enabling energy access • Assessment of land use constraints • Building domestic competency through industry, academia, and technical centers • Development of R&D road map • Creation of a working group focused on supporting public companies to incorporate green hydrogen into their business • Clear governance structure
Is there an existing infrastructure that can be leveraged or re-purposed?	• Build local knowledge, scale, and infrastructure to establish a domestic hydrogen ecosystem before tapping into export markets. • Accelerate the deployment of green hydrogen in six prioritized applications to build local supply chains and acquire experience. • Review natural gas regulation and infrastructure to promote the introduction of green hydrogen quotas.
Are there favorable conditions, geographic positioning and resources that can create competitive advantages?	• Electricity produced with low-cost renewable resources (solar, wind). • The increasing availability of green financing, strong corporate commitments to decarbonization, and the existing tax benefits for remote regions. • Solid institutional framework, innovation ecosystem, non-discriminatory investment rules, and transparent openness to trade allowed development of internationally competitive and dynamic economic sectors.
What are the guiding principles for green hydrogen deployment?	1. Mission-oriented policy 2. Efficient pathway to a net zero country 3. Green hydrogen as a catalyst for local growth 4. Openness to the world 5. New economy based on clean exports 6. Balanced use of resources and land

[a] REN21, "Renewables 2022 Global Status Report Chile Factsheet," 2022, https://www.ren21.net/wp-content/uploads/2019/05/GSR2022_Fact_Sheet_Chile.pdf.

Instruments and Mechanisms

- Hydrogen tax incentives are not detailed in the national strategy. Nevertheless, Chile has set CO2 emissions (green taxes) and diesel taxes from 2014 and 2020, respectively. Additionally, there are precedents of tax incentives with renewable energies. An example is Law No. 25.019 of Wind and Solar Energy, which states "Capital investments with deferred payment of Value Added Tax (VAT) for a term of 15 years from the enactment of the law."[d]
- While there are no official hydrogen-specific subsidy programs, the Chilean Economic Development Agency (CORFO) launched a $1 billion fund to support the de-risking of several projects.[e] The fund is supported by the European Investment Bank, KfW, the World Bank, and the Inter-American Development Bank. The World Bank's contribution is a $150 million loan, which aims to raise additional resources from the private sector. Notably, CORFO is an active member of the World Bank Hydrogen for Development (H4D) program.
- The national strategy includes the review of natural gas regulation and infrastructure to promote the introduction of green hydrogen quotas, but details or targets for this are still pending.
- According to the World Bank Renewable Indicators for Sustainable Energy (RISE) dashboard, Chile scores high (84 out of 100) for its incentives and regulatory support for renewable energy. Specifically, Chile offers long-term power purchase agreements for small-scale renewable electricity producers and has published clear and practical guidance on the permissions required to develop a renewable energy project.[f]

- Chile has had a carbon tax in place since 2017 when they divided CO_2 emissions across 9 sectors. In 2023, Chile published regulations to govern the offset mechanism under carbon tax. The government is also considering increasing the tax rate to apply a carbon tax to the electricity sector.[g]

Regulatory Environment

- As is the case with most countries, Chile does not have a clear definition of what qualifies as green hydrogen. Law 21305 on energy efficiency does, however, include hydrogen as an energy source and a feedstock for different fuels, perhaps laying the groundwork for specific application in the energy sector.[h]
- According to the World Bank Renewable Indicators for Sustainable Energy dashboard, Chile scores high (80 out of 100) for its legal framework for RE, which allows for private sector ownership of RE generation, includes an official RE target linked to international commitments, and governed by a renewable energy action plan to achieve the target.[i]
- No certification programs have been implemented in Latin America, but a 2022 report from the World Bank and Hinicio recommends that should Chile adopt or develop an approach, it should be aligned with the European Guarantees of Origin (CEN/EECS) and Renewable Fuels of Non-Biological Origin (RFNBOs). The report also provides a strategy for Chile to develop a certification strategy.[j]
- Safety and technical standards. Chile defines hydrogen as a "dangerous substance", and its strategy lays out relevant action items related to standards and safety.[k] In early 2022, the government published the Safety Regulation for Hydrogen Facilities, (per Supreme Decree No. 13), which establishes minimum safety requirements for hydrogen facilities using hydrogen as an energy carrier.
- Regulation for hydrogen blending. Chile's National Congress has discussed a bill that would regulate blending hydrogen into the gas grids, which it intends to begin implementing after 2028 (up to 20 percent).[l]

Private Sector Ecosystem

- Chile announced some 60 green hydrogen projects (as of February 2024), mostly concentrated in the north (Antofagasta) and south (Magallanes). Chile could produce up to 160 Mt per year of green hydrogen by 2040 and become a leading low-cost green hydrogen producer in the world.[m]
- Chile has a very active green hydrogen industry association — H2Chile — which was founded in 2018 and includes over 90 private sector members covering the entire value chain.[n]

a. International Energy Agency (IEA), Global Hydrogen Review 2023.

b. Government of Chile, "Chile's Nationally Determined Contribution," 2020, https://unfccc.int/sites/default/files/NDC/2022-06/Chile%27s_NDC_2020_english.pdf.

c. Government of Chile, National Green Hydrogen Strategy, 2020, https://energia.gob.cl/sites/default/files/national_green_hydrogen_strategy_-_chile.pdf.

d. IEA, "Argentina Law 25.019 on the Promotion of Wind and Solar Energy," last updated March 18, 2018, https://origin.iea.org/policies/4657-argentina-law-25019-on-the-promotion-of-wind-and-solar-energy.

e. Hydrogen Insight, "Chile Tops Up Green Hydrogen Fund to $1bn and Pledges to Protect Producers against Certain 'Financial Risks,'" June 20, 2023, https://www.hydrogeninsight.com/production/chile-tops-up-green-hydrogen-fund-to-1bn-and-pledges-to-protect-producers-against-certain-financial-risks/2-1-1470847.

f. World Bank ESMAP, Regulatory Indicators for Sustainable Energy (RISE): Chile, n.d., https://rise.esmap.org/country/chile.

g. World Bank, "State and Trends of Carbon Pricing 2023," 2023, https://openknowledge.worldbank.org/entities/publication/58f2a409-9bb7-4ee6-899d-be47835c838f.

h. Government of Chile, "Ley 21305 sobre eficiencia energética, 2021, https://www.bcn.cl/leychile/navegar?idNorma=1155887.

i. World Bank ESMAP, RISE: Chile.

j. Hinicio and World Bank, "Deliverable 4: Advisory Report on the Development of a Green Hydrogen Certification Scheme in Chile," 2022, https://hinicio.com/wp-content/uploads/2022/08/Hinicio_green_hydrogen_certification_report_Chile_WB.pdf.

k. Zhiyuan Fan et al, "Hydrogen Leakage: A Potential Risk for the Hydrogen Economy (energy policy commentary, Columbia University, 2022), https://www.energypolicy.columbia.edu/wp-content/uploads/2022/07/HydrogenLeakageRegulations_CGEP_Commentary_063022.pdf.

l. Government of Chile, National Green Hydrogen Strategy.

m. International Trade Administration, "Chile Energy Green Hydrogen," 2021, https://www.trade.gov/market-intelligence/chile-energy-green-hydrogen.

n. H2Chile, "Quienes Somos," 2023, https://h2chile.cl/quienes-somos/.

PILLAR 2: SUPPLY CONDITIONS

Table 3.8 shows conditions that increase the supply of green hydrogen.

To understand the supply side of the hydrogen value chain, it helps to first understand hydrogen's physical properties (box 3.4). Hydrogen is a light, energy-dense gas. Because of its high reactivity, on Earth it is typically found bonded to other elements. Today, production is confined to its extraction from water (electrolysis) or fossil fuels (methane reforming). Both processes incur large energy losses. Moreover, because of its low density, hydrogen must be compressed for transport, making its shipping and storing costlier than those for natural gas. Increasing the pressure of hydrogen compensates but also costs energy, which increases landed costs. Similarly, liquefying hydrogen helps reduce its volume yet requires a lower temperature than natural gas. This also has significant energy and monetary costs. Converting hydrogen to its derivatives can help realize more value. Once hydrogen is converted to ammonia (NH_3) or other derivatives, its energy density increases, facilitating long-distance transport and long-term storage and leveraging the existing shipping infrastructure for the transport of ammonia—ultimately contributing to global decarbonization.

Table 3.8

Robust Supply Conditions

Robust Supply Conditions	Access to renewable energy	Installed RE
		Potential RE
		Grid availability
	Infrastructure	Water availability
		Access to critical raw materials (CRMs)
		Existing industrial infrastructure
		Existing NG infrastructure
		Bulk chemical export
		Existing deep-water ports
		Storage facilities
	Value chain readiness	Electrolysis/FC/FCEV manufacturers
		Industrial gas companies
		Energy utility/oil and gas company with hydrogen experience
		Chemical companies with hydrogen experience
		EPC companies with hydrogen experience
		Active relevant business association/network(s)
		# hydrogen projects (operational or under development)

Source: Original table for this publication.

Note: EPC = engineering, procurement, and construction; FC/FCEV = fuel cell/fuel cell electric vehicle; NG = natural gas; RE = renewable energy.

There are three main elements to the supply side of the green hydrogen value chain. They are renewable energy (used to power electrolyzers), infrastructure (to store, transport, and transform green hydrogen molecules as needed), and end use applications, including domestic gas, energy, chemical, manufacturing, and EPC companies as well as relevant business associations and existing hydrogen projects **(figure 3.4)**. Understanding the elements contributing to strong supply conditions is essential to determining a project's or market's readiness and attractiveness at later stages, specifically offtake. All stages of the green hydrogen value chain represent a significant risk. However, producers face more risks than other parts of the value chain.

Access to renewable energy

Cheap, plentiful, and consistently available renewable energy is the single most important ingredient in green hydrogen production.

- *Cheap:* Electricity costs account for up to 55 percent of total project costs, making or breaking project bankability.
- *Plentiful:* Countries with high RE resource availability (and existing or planned deployment) are best positioned to develop green hydrogen projects.
- *Consistently available:* Green hydrogen production requires electricity sourced from a reliable and highly available low-emission supply, such as a combination of solar PV and battery storage, to account for variation **(box 3.5)**.

The amount of new renewable energy required to produce green hydrogen at the necessary scale is daunting. In the Net Zero Emissions Scenario, by 2030, of the 150 million metric tons of the total global hydrogen demand, 51 must be classified as green or low emissions **(figure 3.5)**.[52] By 2050, green hydrogen production at 327 million metric tons is projected to meet the global demand of 430 million metric tons. Today, less than 1 percent of annual hydrogen production can be categorized as green.

BOX 3.4

Distinguishing Supply Side Versus Demand Side Value Chain Components

- In a market that produces hydrogen gas without transformation into synthetic fuels or ammonia, supply-side conditions would stop at production.
- From production to consumption, the value chain includes multiple elements closely dependent on and linked with the broader chemicals and energy sectors. Similarly, each value chain segment hosts distinctive technologies, suitable applications and costs, market players, and investment needs for further commercialization.
- As the global green hydrogen market develops, value chains will become clearer and easier to understand.

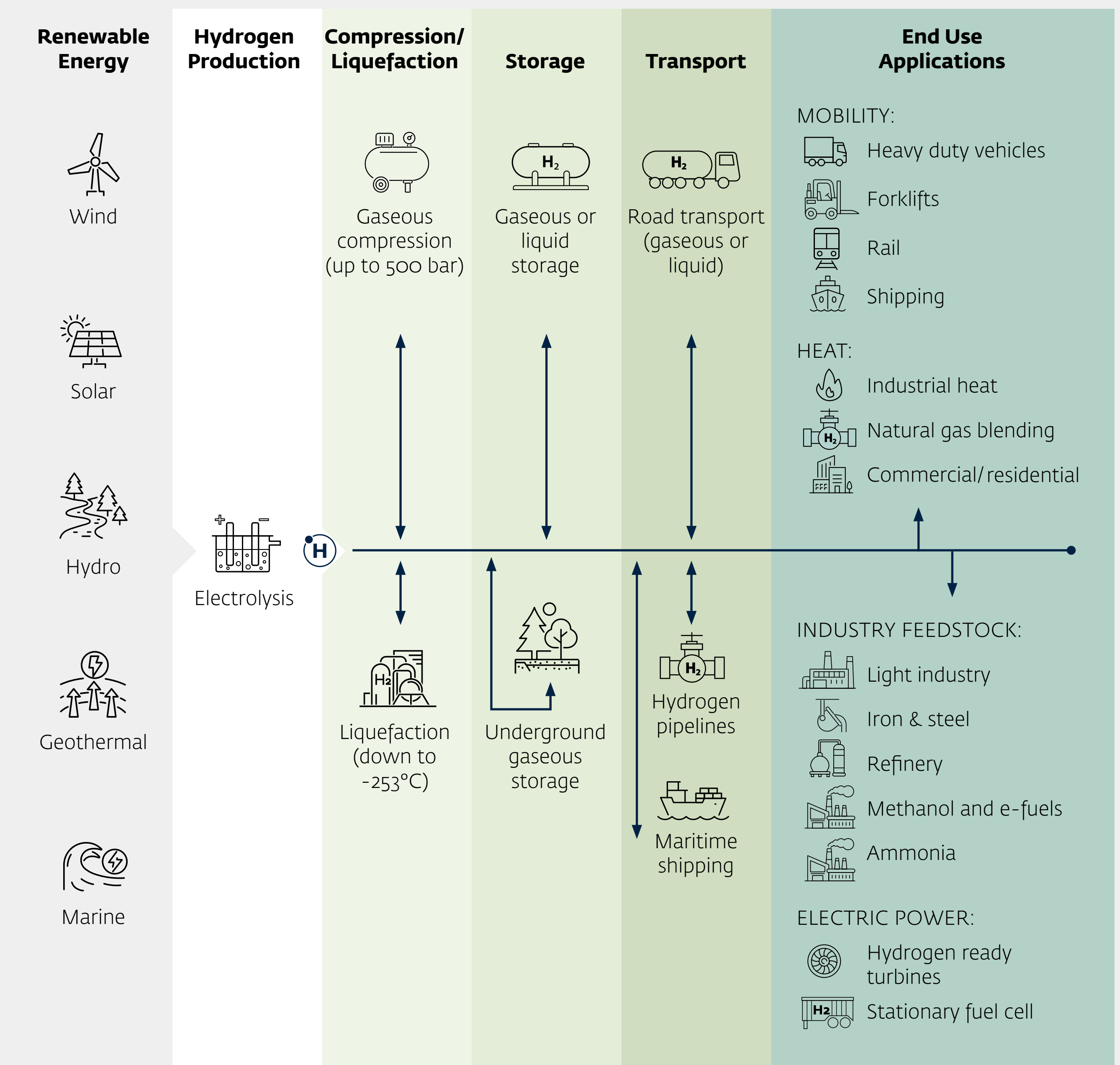
Source: Original figure for this publication.

In this same scenario, 99.7 percent of total global generation for hydrogen production and all other uses must be from low-emissions sources. The bottom line is that to meet these goals, the world will need to deploy three times as much renewable energy by 2050 as is available today.[53] Thus, the availability of renewable energy is a key factor when evaluating a market for green hydrogen production potential.

As of the end of 2023, total renewable energy capacity worldwide reached 3,870 gigawatts **(figure 3.6)**.[54] Emerging markets account for up to 50 percent of the global share, with China dominating the market at 1,453 gigawatts, while Brazil (194 gigawatts) and India (176 gigawatts) take the third and fourth places after the United States (387.5 gigawatts). Emerging markets are well positioned to harness the leadership potential of renewable energy deployment, but they will require coordination among a variety of actors

FIGURE 3.4

Green Hydrogen Value Chain



Source: Original figure for this publication.

BOX 3.5

The Utilization Rate Challenge

Clean and cheap energy is not sufficient—the renewable energy source must also be able to power the electrolyzer for as many hours a day as possible, maximizing the plant's utilization rate (sometimes also referred to as load or capacity factor).

Fact 1: Electrolyzers are capable of (and happiest when) running 100 percent of the time (24/7/365). However, this is possible only with a steady electricity connection.

Fact 2: Solar and wind energy can be captured only when the sun is shining (20 to 25 percent capacity factor) or the wind is blowing (24 to 40 percent capacity factor for onshore wind). For comparison, other capacity factors are around 70 (hydropower), 80 (coal), 90 (geothermal), and 95 (nuclear) percent.

Challenge: Variable solar and wind energy are not ideal sources for electrolysis and/or 24/7/365 green hydrogen production, but they are the most readily available and with hydro are the cheapest alternatives to fossil fuels in many emerging markets.

Solution: Achieve the highest electrolyzer utilization rate you can by securing renewable energy resources with high-load/capacity factors.

X Non-renewable energy (RE)

X RE + non-RE grid connection

▯ Oversized RE

▯ Oversized RE + battery storage

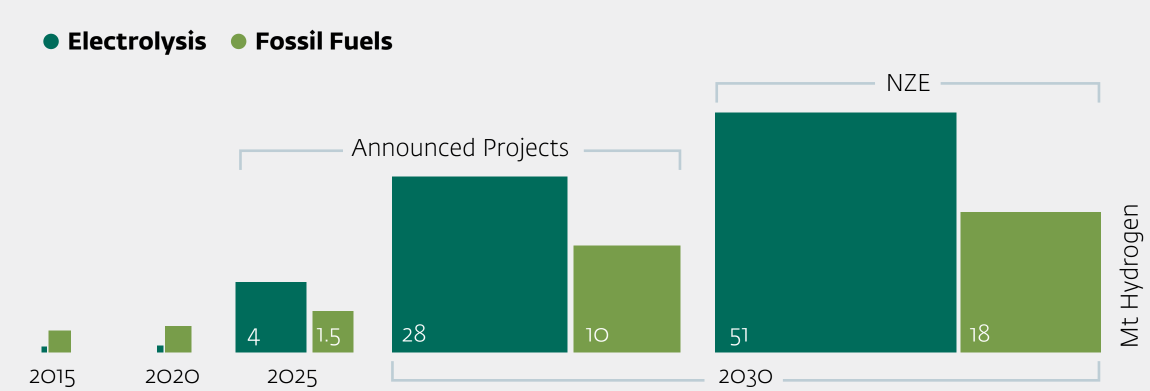
▯ Couple wind and solar

▯ RE + virtual RE power purchase agreement (PPA) grid connection

Source: Original figure for this publication.

FIGURE 3.5

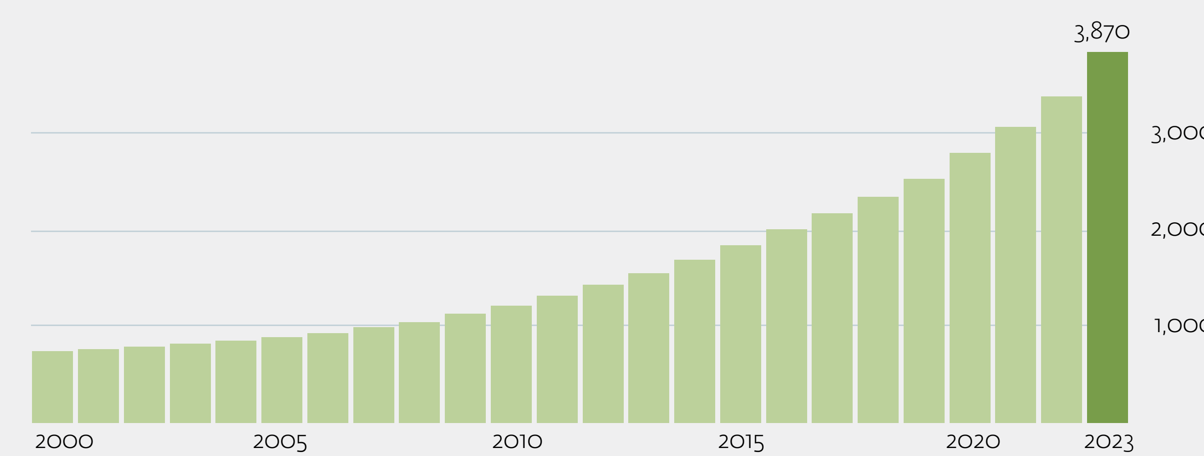
Green and Low-Emissions Hydrogen Production (2015–30)



Source: IEA (International Energy Agency), "Hydrogen: Net Zero Emissions Guide," 2023, https://www.iea.org/reports/hydrogen-2156.
Note: CCUS = carbon capture, utilization, and storage; Mt = megaton; NZE = net zero emissions.

FIGURE 3.6

Total Renewable Energy Capacity Worldwide (GW)



Source: International Renewable Energy Agency (IRENA), 2023.

to ensure that new capacity is developed for the best-use case. Depending on regulatory environments, much of the renewable energy to produce green hydrogen will need to be newly built. Deploying new renewable energy capacity solely to produce green hydrogen may not always be the best choice if a market has low energy access or renewable energy capacity for domestic consumption. Ideally, a country will conduct national studies to gauge renewable energy potential and, in some cases, manage auctions to sell off that potential to project developers. Depending on the model countries decides to pursue, they should coordinate these auctions with green hydrogen production centers, balancing access to electricity at low rates for local residential and industrial customers with the use for generating green hydrogen. If a project is connected to the grid, the grid emissions factor must be considered to understand the carbon intensity of green hydrogen production.

Infrastructure

Four main types of infrastructure are required to support the global green hydrogen economy:

1. *Water (desalination):* According to IRENA (2023), between 17.5 and 22.3 liters of portable water is required to produce 1 kilogram of hydrogen. Locations with readily accessible fresh water are preferred to those that will require zero-carbon desalination facilities. Although desalination does not add much to the final cost (typically $0.05 to $0.10 per kilogram of green hydrogen), it must not compete with water for local populations in arid geographies such as Chile, Mauritania, Morocco, and South Africa. Should desalination be required, it should be powered with renewable energy.

2. *Ports:* Even though globally there are 200 ports capable of storing ammonia, many more will need to be planned according to national development strategies and

constructed within a reasonable timeline to meet green hydrogen production goals.

3. *Storage:* Sufficient storage capacity will be required at both the project and the market levels and must be coordinated at the hourly, daily, and seasonal levels with supply (for example, renewable energy availability) and demand **(box 3.6)**.

4. *Pipelines:* While most natural gas pipelines can be retrofitted for green hydrogen blending and/or replacement, a significant amount of greenfield hydrogen pipeline capacity will need to be built globally.

Significant storage capacity is essential to support a large-scale hydrogen economy, including the hydrogen export-oriented focus of most emerging markets. This need arises because hydrogen is often produced intermittently from renewable sources, necessitating buffer stocks to ensure a continuous supply. BloombergNEF estimates that storage capacity equivalent to 15 to 20 percent of annual hydrogen demand will be necessary, compared to 12 percent for natural gas today. Options include salt caverns, rock caverns, and depleted gas and oil fields, each with advantages and limitations. For example, salt caverns offer low-cost storage but are region specific, while rock caverns and depleted fields require further development and feasibility assessments. If geological storage is unavailable, costly compressed storage solutions will be needed. Meeting mid-century storage needs will be challenging, highlighting the importance of developing diverse and scalable storage technologies.

Hydrogen transportation in pipelines is another distribution option. In addition to the pipeline infrastructure discussed in the next paragraph, hydrogen must be liquefied, compressed, or converted into higher-density energy carriers such as ammonia or synthetic fuels (for example, e-methane or e-methanol), which require additional nitrogen or carbon dioxide feedstock. Liquid organic hydrogen carriers offer another method, using specific carrier liquids.[55] These transformations enhance hydrogen's energy density and economical transport viability, but they are energy intensive. Research is ongoing to improve conversion efficiency but challenges due to the fundamental physics of volumetric density, energy requirement for liquefaction temperature, and the need to repurpose existing natural gas pipelines persist.

BOX 3.6

Parameters for Comparing Storage Options

- Working capacity
- Cost ($/kg)
- Flexibility
- Losses (% H2 lost/year) and related GHG considerations
- Parasitic load (% H2 HHV)
- Density (kg/m3)
- H2 purity after release
- Geographical availability
- Technological readiness
- Commercial readiness
- Social acceptability
- Safety concerns

Source: BloombergNEF.
Note: GHG = greenhouse gas; H2 = hydrogen; HHV = lower heating value.

With distribution accounting for around two-thirds of the final cost of hydrogen to the customer, delivery mechanisms dictate competitiveness. Transport costs depend on the volume of hydrogen transported, the distance between production and demand points, the transport means used, and the state in which hydrogen is transported (gaseous, liquefied, or synthesized in chemical carriers). Moreover, the financing costs of the infrastructure must be added to the operational costs. In general, trucks are the best choice for low volumes and medium distances (50 to 200 kilometers), pipelines are usually best for large volumes and distances (more than 500 kilometers), and ships are best for large volumes and long distances (more than 500 kilometers).[56] Moreover, retrofitting existing natural gas pipelines could further improve the cost advantage. However, there exists only about 5,000 kilometers of hydrogen pipelines globally, mainly in industrial clusters in Asia, Europe, and North America. Cross-border cooperation—as seen with the European Hydrogen Backbone initiative[57]—will be essential to connecting supply with demand centers.

Another approach to consolidating production with demand is the concept of hydrogen hubs or valleys. The US Department of Energy H2Hubs program and the EU Mission Innovation Hydrogen Valleys program are the most robust to date. The US. government has allotted $8 billion to establish 6 to 10 regional hubs across the country.[58] The Department of Energy reviewed nearly 80 concepts and recommended that 33 applications be continued. The Hydrogen Valley Platform is a global collaboration initiative of 23 countries and the European Commission on behalf of the European Union; it aims to facilitate the creation of integrated hydrogen projects through knowledge sharing and matchmaking. The website includes information about 98 hydrogen valleys in 33 countries, amounting to a total investment of €125 billion **(map 3.2)**.

Value chain development

Companies with existing hydrogen experience will have an early advantage, and many are actively building up their capacity.

Five main types of companies are involved in the supply side of the value chain:

- Electrolyzer and fuel cell manufacturers
- Industrial gas companies
- Energy utilities/oil and gas companies
- Chemical companies
- EPC companies

Although electrolyzer technology is more than a century old, it has never been tested, manufactured, and deployed at the scale required for the green hydrogen market of the future. The anticipated surge in green hydrogen demand is expected to spur innovation in this sector. Meeting the ambitious targets set by IEA's 2050 Net Zero Emissions Scenario requires a massive shift in electrolysis capacity. By 2030, the total installed electrolysis capacity must reach 560 gigawatts, from 2.9 gigawatts in 2023.[59] Despite a fourfold increase from a year before, there is a long way to go. As more countries set their green hydrogen ambitions, an opportunity for manufacturers to scale up their presence, including in emerging markets beyond China and India (the only developing countries with electrolysis manufacturing capacity), is presented. Amid this growth, the industry faces critical decisions on technology adoption. The choice between alkaline and proton exchange membrane (PEM) electrolyzers remains pivotal. Yet basing business decisions mainly on early assumptions is full of uncertainty. The absence of standardized test protocols hinders accurate performance comparisons across technologies. Pricewise, Chinese-produced alkaline is the most affordable option. Production of electrolyzers (alkaline, PEM, and using other technologies such as solid oxide) in North America and Europe is expected to level the competition by the 2030s. Other technologies will continue to evolve, driven largely by the need for electrode or catalyst materials that don't rely on expensive or rare materials and have long lifetimes in alkaline or acid chemical conditions **(box 3.7)**.

Major oil and gas industry players have expanded their business to include hydrogen production, building on synergies with their core business, yet they still comprise only a small share of the market. International oil giants reportedly hold just 8 percent of global green

MAP 3.2

Countries with Hydrogen Valley Activities

● **Countries with ongoing Hydrogen Valley activities**

United Kingdom
- HyNet North West
- BIG HIT Orkney Islands

Netherlands
- HEAVENIN
- Hydrogen Delta
- Europe's Hydrogen Hub: H2 Proposition Zuid-Holland/Rotterdam

Belgium
- Flemish Hydrogen Ports Valley

Germany
- H2Rivers
- HyBayern
- eFarm
- Northern German Living Lab
- Hyways for Future

Italy
- Hydrogen Valley South Tyrol
- H2iseO Hydrogen Valley

Denmark
- HyBalance

Austria
- WIVA P&G: Hydrogen Flagship Region

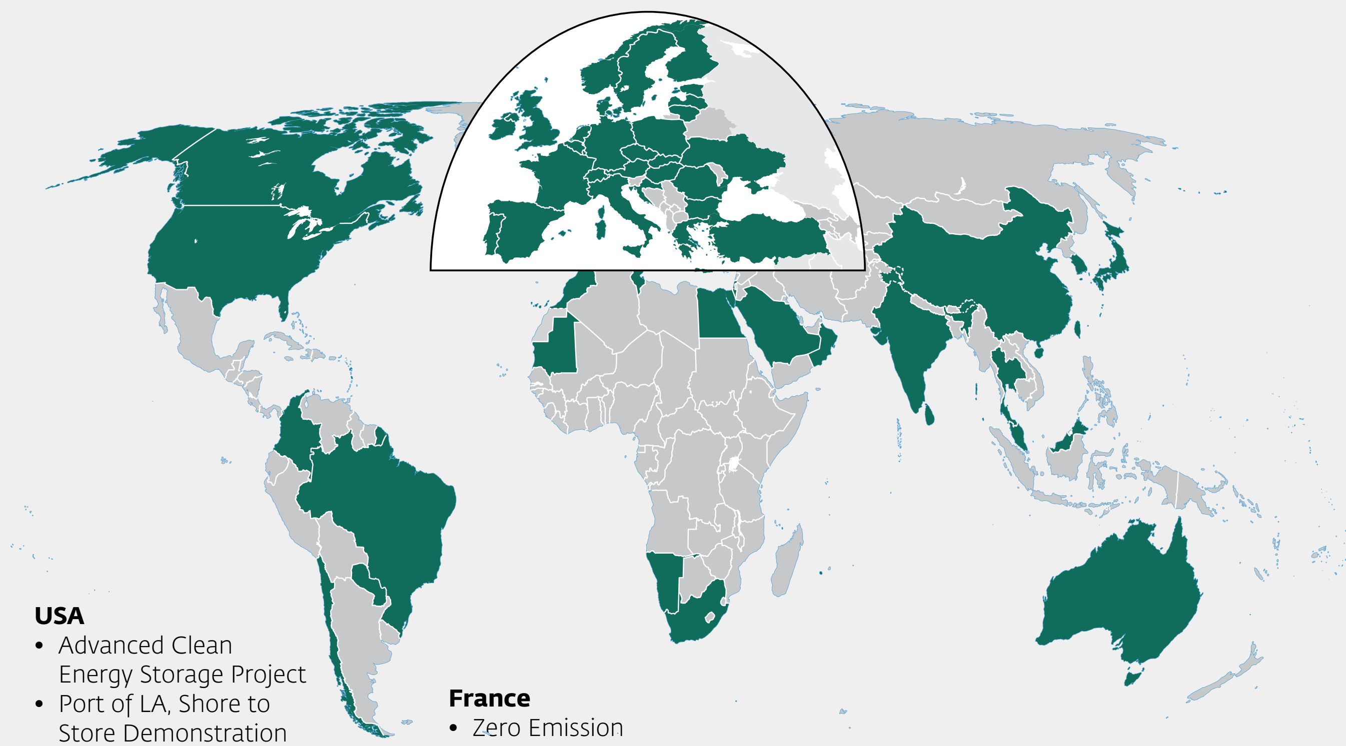
Portugal
- Sines Industrial Hub

Spain
- Green Hysland
- Basque Hydrogen Corridor

Japan
- FH2R Fukushima

China
- Foshan Nanhai Xianhu Lake Hydrogen Valley Town
- Zhangjiakou Demonstration Project
- Rugao Hydrogen Energy Town

Thailand
- Phi Suea House



USA
- Advanced Clean Energy Storage Project
- Port of LA, Shore to Store Demonstration Project
- Wyoming Clean Power Center

Chile
- Hydrogen Facility Initiative

France
- Zero Emission Valley
- Normandy Hydrogen
- Hydrogen Territory Bourgogne Franche Comté
- Centrale Electrique de l'Ouest Guyanais

Oman
- Green Hydrogen and Chemicals Oman

Australia
- Crystal Brook Hydrogen Superhub
- Eyre Peninsula Gateway

Source: European Commission, Going Global: An Update on Hydrogen Valleys and Their Role in the New Hydrogen Economy, 2022, https://h2v.eu/hydrogen-valleys.

Box 3.7

Electrolyzer Technologies: No Clear Winner

There is no standard "better" choice for one type of electrolyzer over another—it all depends on the project specifics. The main factor is demand response, or the amount of time it takes to ramp hydrogen output up or down according to changes in electricity supply, a feature that would make a technology better suited to variable renewable energy.

Literature suggests that PEM electrolyzers tend to have a faster demand response than alkaline; however, it is not significant or widely tested enough to merit generalizations.

The best technology choice depends on the project's specific context. Examples include land availability (proton exchange membrane, PEM, has a smaller footprint), voltage (low voltage reduces yield purity and can lead to explosion in alkaline electrolyzers), expected end use, economics (Chinese alkaline is generally cheaper), and other factors.

In the long run, the technology with the strongest momentum in mass manufacturing will generally win, even if not superior on performance.

Source: Original figure for this publication.

or low-carbon hydrogen capacity as of late 2023,[60] with Equinor, BP, Shell, and TotalEnergies owning the largest shares of announced green hydrogen capacity.

The oil and gas companies will consume some, but not all, of this capacity. Equinor leads the pack with its H21 North of England project to power, with emission-free hydrogen, 3.7 million homes and 40,000 businesses by 2034. TotalEnergies announced a replacement of 500,000 metric tons (or 0.5 million tons) of gray hydrogen use in its refineries per year by 2030.[61] It is possible that these announcements were spurred by the EU's recently announced hydrogen quotas,[62] of which TotalEnergies' capacity would account for 2.5 percent.[63] The oil and gas majors are taking a conservative view and upgrading existing refineries to green hydrogen until a premium price is established, starting with small-scale projects prior to 2030 before ramping up at industrial scale.

The next segment in the value chain, the chemical industry, accounts for the most high-potential hydrogen offtakers and will continue to do so in the near term. Hydrogen is used to produce ammonia, fertilizers, and various organic compounds. It is also an essential material in several chemical manufacturing processes. The green hydrogen market for chemical companies was valued at $42 billion in 2023 and is expected to grow at a rate of 5.6 percent through 2032.[64] Chemical companies represent the demand side of the value chain essential to generating supply. Financing production without a buyer is one of the largest risks for projects. Since these companies already consume gray hydrogen, they are best positioned to purchase green alternatives, mostly for oil refining, ammonia, and methanol production. As of 2023, the chemicals sector accounted for two-thirds of announced green hydrogen projects.

Several prominent international and regional associations are dedicated to advancing the hydrogen industry (table 3.9). These associations play crucial roles in promoting green hydrogen technologies, advocating for supportive policies, facilitating collaboration, and disseminating information. The Hydrogen Council, launched at the World Economic Forum in Davos in 2017, brings together more than 140 companies, governments, investors, and members of civil society worldwide. The council aims to drive investments, foster stakeholder collaboration, and advocate for supportive policies to scale hydrogen technologies across industries and regions. The International Association for Hydrogen Energy (IAHE) is a nonprofit organization dedicated to advancing the global hydrogen

TABLE 3.9

Sample Hydrogen Industry Associations

Global	Hydrogen Council	https://hydrogencouncil.com/en/
	Hydrogen for Development (H4D)	https://www.esmap.org/Hydrogen_for_Development_Partnership_H4D
	International Association for Hydrogen Energy (IAHE)	https://www.iahe.org
	Green Hydrogen	https://gh2.org/
Regional	African Hydrogen Partnership	https://ahp.africa
	Hydrogen Europe	https://hydrogeneurope.eu/
	Asia-Pacific Hydrogen Association	https://apac-hydrogen.org/
	H2LAC	https://h2lac.org/
National	Hydrogen Egypt	https://www.hydrogenegypt.com/
	Chile Hydrogen Association	https://h2chile.cl/
	India Hydrogen Alliance	https://ih2a.com/
Subnational	California Hydrogen Business Council	https://californiahydrogen.org

Source: Original figure for this publication.

energy community. Founded in 1974, the IAHE serves as a platform for collaboration, knowledge exchange, and advocacy in hydrogen energy. Its membership includes researchers, engineers, policy makers, industry professionals, and other stakeholders worldwide. Industry associations at the regional and national levels are also significant in forming alliances and managing challenges related to storage and transport from supply centers. Finally, many industry associations hold conventions that bring together stakeholders from all over the world, creating opportunities for knowledge sharing, new partnerships, and business agreements.

BOX 3.8

Case Study 3

Brazil's Green Hydrogen Strategy

Brazil is the ninth-largest economy in the world and the largest in Latin America, with a gross domestic product of more than $2.2 trillion in 2023. It is also Latin America's largest electricity market and the sixth largest globally. Boasting the cheapest and most abundant renewable energy in the region, which accounts for 83 percent of its energy mix (well above the global average of 25 percent), Brazil's renewable energy sector is well-positioned for continued growth. Its regulatory frameworks and private sector engagement support the development of sustainable solutions, including green fertilizer, clean fuels such as sustainable aviation fuels, energy storage, hydrogen, and wind power projects. The country's green hydrogen ambition is to decarbonize its industrial sectors and become the most competitive producer of green hydrogen in the world **(table B.3.8.1)**.

TABLE B.3.8.1

Key Statistics: Brazil

Hydrogen Strategy	Programa Nacional do Hidrogenico (PNH2) published July 2021 by the Ministry of Mines and Energy			
Energy Mix (2022)		INSTALLED	UNTAPPED	
	Wind	25.6 GW	288.4 GW	
	Solar PV	24.1 GW	282.9 GW	
	Hydro	109.8 GW	66.2 GW	
Existing Electrolysis Projects	ANNOUNCED	FINANCED	OPERATIONAL	
	14	1	1	
Top 4 Hydrogen Projects by Volume	COMPANY	PROJECT NAME(S)	ESTIMATED HYDROGEN OUTPUT (metric tons/year)	INTENDED USE
	Energix Energy Pty Black & Veatch	Energy Base One	300,000	Export
	Unigel Comercial SA Thyssenkrupp Nucera AG & Co KGaa	Camaçari	75,000	Shipping, steel production, oil refining, ammonia production
	Shell PLC	Port of Açu	1,320	Oil and gas
	EDP	Port of Pecém	61	Power turbine

Source: Data from Hinicio, BloomberNEF (2022).
Note: GW = gigawatt; PV = photovoltaic.

Access to renewable energy

- Installed and potential renewable energy. Brazil accounts for almost 7 percent of global renewable energy production and has paved the way in biofuels and hydropower.[a] As of 2022, more than 80 percent of its electricity demand was met by renewables, including hydropower, making it one of the world's cleanest grids.[b] Developing the wind energy sector in Brazil, which has one of the best average onshore wind capacity factors in the world, is at the center of the country's green hydrogen strategy. Brazil has nearly 300 gigawatts of untapped wind energy potential and the cheapest renewable energy in Latin America,[c] followed by Chile.

Infrastructure

- About 20% of the world's water supply belongs to Brazil, making it abundant for green hydrogen production, whereas neighboring nations Chile and Argentina face water availability issues that may worsen in the next decade.[d]
- Rich with natural resources, Brazil enjoys deposits of all five critical raw materials (iridium, platinum, tantalum, cobalt, and nickel).
- Brazil has developed green hydrogen clusters dedicated to exports within port areas, such as Port of Acu, Pecem Industrial Port Complex. Projects not only benefit from tax discounts and exemptions but also leverage the port's infrastructure to facilitate the transportation and export of green hydrogen.
- Brazil has an existing domestic supply chain for wind farm components.
- The country's availability of existing industrial and shipping infrastructure (table B3.8.2) is especially beneficial.

Brazil claims 9,409 kilometers of existing natural gas infrastructure (unclear if it is able to withhold hydrogen blending), 36.9 kilotons of ammonia and methanol exports per year, and 11 active deep-water ports.[e]

TABLE B3.8.2

Available Infrastructure

Refining potential yearly hydrogen use (based on capacity)	557 kiloton/year
Ammonia production capacity	363 kiloton/year
Potential yearly hydrogen use (based on capacity)	620 kiloton/year

a. Simon Bennett et al., "Brazil Aims to Make a Global Impact on Clean Energy Innovation," IEA, April 11, 2023, https://www.iea.org/commentaries/brazil-aims-to-make-a-global-impact-on-clean-energy-innovation.

b. Government of Brazil (website), "Brazil Publishes National Hydrogen Program," updated September 2, 2022, 11:13, https://www.gov.br/en/government-of-brazil/latest-news/2022/brazil-publishes-national-hydrogen-program.

c. Peter Millard, "With Plenty of Clean Energy, Brazil Aims for Green Hydrogen Export Market," Bloomberg, updated June 29, 2023, https://www.bloomberg.com/news/features/2023-06-29/brazil-aims-for-green-hydrogen-market-fueled-by-wind-energy.

d. World Resources Institute, "Aqueduct Projected Water Stress Country Rankings," August 26, 2015, https://www.wri.org/data/aqueduct-projected-water-stress-country-rankings.

e. Empresa de Pesquisa Energetica (website) https://www.epe.gov.br/sites-pt/sala-de-imprensa/noticias/Documents/ESTANDE%20-%20Natural%20Gas%20Infrastructures%20in%20Brazil%20and%20South%20America.pdf

PILLAR 3: DEMAND CONDITIONS

Table 3.10 offers an example of conditions for increasing demand for green hydrogen.

Hydrogen, as a versatile energy carrier, has been long used for a range of industrial applications, including:

- *In oil refining* to remove sulfur and other contaminants from fuels by chemical separation when making products such as gasoline;
- *In chemical production,* in which hydrogen serves as a feedstock to produce ammonia and methanol, among other chemicals; and
- *As a reducing agent* for the steel industry, to produce direct reduced iron.

Global hydrogen use reached 95 million metric tons in 2022, a 3 percent increase from 2021, concentrated in established applications, such as oil refining and the chemical sector. Refineries use approximately 38 million metric tons of hydrogen annually,[65] while roughly two-thirds of demand in the industry is for ammonia production.

To meet the Net Zero Emissions Scenario, with the transition of the sector from fossil fuel–based to low-emission hydrogen, green hydrogen becomes an attractive option for new uses. It is well-positioned to help decarbonize hard-to-abate sectors and for energy storage. Emerging hydrogen applications include iron making, chemicals, long-distance transport, aviation and shipping, long-duration energy storage and generation, and high-temperature industrial heating. Other potential applications may not offer a competitive advantage because of the existence of more efficient low-emission alternatives for their use.

Hydrogen combustion generates heat that industries need, including for manufacturing processes for plastics, cement, and glass. Although electricity can also be used for high-grade heat, that option entails redesigning industrial equipment and therefore capital expenditures. Hydrogen can offer an advantage because of the minimal need for redesign. Hydrogen can also be useful in residential and commercial heating, covering the residual heat load at combined heat-and-power plants. As of today, however, hydrogen uses in industry for high-temperature heat are still at the prototype stage for most technologies, notably steam boilers. That is why heating makes up the smallest share of

TABLE 3.10

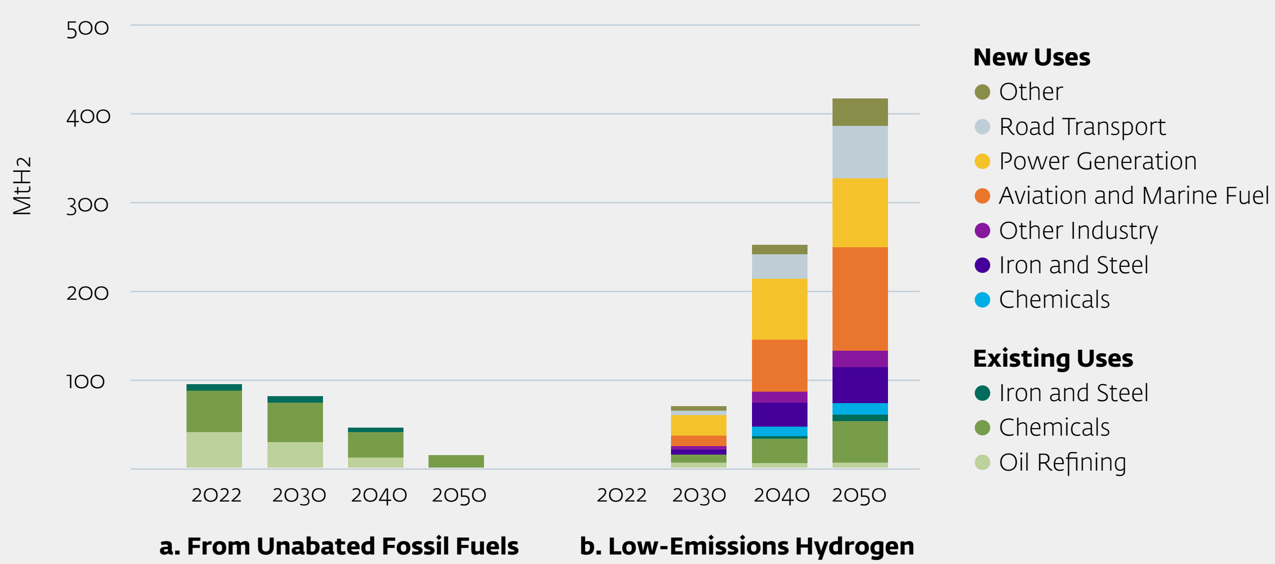
Attractive Demand Opportunity

Attractive demand opportunity	Domestic H2 demand	Current
		Projected
	Export potential	Bilateral conversation/agreements
	Competitiveness	Natural gas costs
		Diesel costs
		Alternative decarbonization technologies

Source: Original figure for this publication.

FIGURE 3.7

Global Hydrogen Demand (IEA Net Zero Scenario, 2022–50)



Use of low-emissions hydrogen rises significantly to 70 Mt by 2030 and extends to new applications such as in aviation and shipping

Source: International Energy Agency (IEA), Net Zero Roadmap (Paris: IEA, 2023), https://iea.blob.core.windows.net/assets/6d4dda5b-be1b-4011-9dad-49c56cdf69d1/NetZero-Roadmap_AGlobalPathwaytoKeepthe1.5CGoalinReach-2023Update.pdf.

Note: MtH_2 = million tonnes of hydrogen. Unabated fossil fuels include hydrogen produced with CO_2 capture for utilization without storage, such as in urea synthesis. Demand for aviation and marine fuel and power generation includes hydrogen that is converted to make low-emissions hydrogen-based fuels.

hydrogen applications, with less than 10 percent of overall hydrogen demand 2050 (see **figure 3.7** for projected global hydrogen demand and potential uses).

Hydrogen's portability and versatility as an energy carrier will help generate power and promote sector coupling. Thanks to its unique ability to store energy for long periods and in large quantities, hydrogen will help even out the intermittency of renewables and extend their use in remote applications. This will help increase the reliability of electricity systems by providing flexibility and peaking services, allowing systems to adjust to demand and supply variability. Moreover, hydrogen, combined with biogenic carbon or CO_2 extracted from the air, can be converted into liquid energy carriers, such as e-gasoline, e-diesel, or e-kerosene, in the transport sector. These clean, electricity-derived, drop-in hydrocarbon fuels then react in fuel cells to power electric motors in energy-intensive transport segments. Those segments, which include trucking, aviation, and shipping, have limited decarbonization options—and the lack of alternatives makes the relatively low conversion efficiency acceptable. Many of these applications are already available and expected to scale up in a few years.

National hydrogen demand

Policy makers must implement hydrogen-specific policies through clear net zero targets and commitments to demonstrate the government's focus and the extent of its ambition. These policies should outline the government's long-term plans, articulated through net zero emissions targets or commitments. Such clarity instills confidence in the market and serves as a catalyst for the adoption of green hydrogen in challenging sectors. In crafting these policies, policy makers must address critical questions, including the target capacity of green hydrogen and the timeline for its operationalization.

To stimulate demand, a balanced approach of incentives and regulations is necessary and should prioritize the reduction of carbon emissions at the most efficient cost rather than simply maximizing hydrogen usage at all costs. Notably, countries responsible for nearly 70 percent of global emissions have either legislated a net zero target or expressed official commitments toward achieving it. Additionally, discussions on emission reduction targets are underway in markets covering the remaining third of global emissions.

More recently, the European Union's 27 member states unanimously adopted the Renewable Energy Directive, which aims to elevate the share of renewable energy in the EU's overall energy consumption to 42.5 percent by 2030, with an additional 2.5 percent indicative enhancement to achieve a 45 percent target. Significantly, the directive mandates that 42 percent of industrial hydrogen consumption be green by 2030, escalating to 60 percent by 2035. This directive has catalyzed a substantial demand, projecting approximately 4 million metric tons of green hydrogen required by 2030.[66]

By 2050, green hydrogen is expected to dominate the global supply, accounting for 50 to 65 percent of the mix because of cost reductions in renewables and electrolyzers. Blue hydrogen will comprise 20 to 35 percent of the total production, concentrated in regions such as the Middle East and North America that have cost-competitive natural gas and carbon capture, utilization, and storage facilities. Blue hydrogen production may require around 500 billion cubic meters of natural gas and the capacity to capture and store 750 to 1,000 million tons of CO_2. Green hydrogen will have a greater share in areas with abundant renewable resources, such as Australia and Chile, but the availability of renewable power could limit its production. Achieving the necessary scale for green hydrogen will require significant investment and large-scale deployment of electrolyzers, as well as national policies and regional and interregional collaboration.[67]

The availability of robust policy frameworks and regulations for hydrogen markets can support the development of strong domestic markets and export strategies. Policies geared toward hydrogen demand—such as contracts for difference and establishment of greenhouse gas emissions standards for natural gas power plants and heavy-duty vehicles—provide developers with the additional certainty they seek. Market-based instruments such as carbon markets can also provide economic incentives through the sale of carbon credits to make green hydrogen financially attractive. Considerable demand is captured in robust national hydrogen strategies and substantial involvement in industries lacking decarbonized alternatives—such as chemicals, steel, refining, and heavy-duty transportation. Case study 4 further highlights India's domestic demand landscape.

Export potential

By 2050, global hydrogen demand could reach 9,000 terawatt-hours, analogous to current renewable energy output. Countries with limited renewable energy potential, such as Germany, Japan, and Korea, will need to import hydrogen, necessitating international production and transport infrastructure. These investments will occur primarily through international partnerships, with a growing number of bilateral and trilateral agreements forming between export and import nations[68].

More than 40 percent of countries with hydrogen strategies are poised to export hydrogen. As discussed previously, nearly half of the countries with green hydrogen strategies and the vast majority of countries in emerging markets have integrated their domestic production targets to export part of their future capacity overseas. For instance, Argentina aims to achieve exports of 4 million metric tons by 2050, Sri Lanka plans to harness 4 gigawatts of offshore wind power by 2030 to produce hydrogen for export, and Kenya, in its newly unveiled strategy, seeks to leverage its strategic geographic position as a regional trading hub. The goal is to commence hydrogen exports within the region once a domestic market for green hydrogen derivatives has been established.[69]

For export-oriented countries, different factors may contribute to achieving competitiveness:

- *The price of natural gas* as a contributing economic factor to the competitiveness of green hydrogen versus blue and gray hydrogen;
- *Availability of cheap and abundant renewable energy* such as wind, solar, and hydro;
- *Availability and access to land, water, transport interconnections, and resources* to scale production;
- *Distribution Infrastructure* such as coastal access, ports, pipelines, and proximity to demand centers;
- *Stable political environment* and reduced likelihood of geopolitical risks; and
- *Government policy and support,* such as public offtake programs to ensure guaranteed demand or contracts for difference for revenue stabilization.

BOX 3.9

Case Study 4

India's Green Hydrogen Ambitions

India's National Green Hydrogen Mission, with World Bank support, allocated a substantial budget of $2.4 billion to bolster electrolyzer manufacturing and hydrogen production between now and 2030. Although the strategy includes subsidies for up to 450,000 tons of hydrogen production annually, this represents just 9 percent of its ambitious 2030 target of 5 million tons per year (table B3.9.1). With such an ambitious goal in sight, India is anticipated to shift its focus toward implementing policies aimed at stimulating demand. These policies will play a crucial role in incentivizing existing gray hydrogen producers to transition to more sustainable alternatives.

TABLE B.3.9.1

Key Statistics: India

<table>
<tr><td>Hydrogen Strategy</td><td colspan="4">India's Ministry of New and Renewable Energy (MNRE) released the National Green Hydrogen Mission in March 2023, including $2.4 billion to support production, domestic industrial decarbonization, and export of green hydrogen.</td></tr>
<tr><td rowspan="4">Energy Mix (2022)</td><td></td><td>INSTALLED</td><td colspan="2">UNTAPPED</td></tr>
<tr><td>Wind</td><td>41.9 GW</td><td colspan="2">260.1 GW</td></tr>
<tr><td>Solar PV</td><td>62.8 GW</td><td colspan="2">685.2 GW</td></tr>
<tr><td>Hydro</td><td>52.0 GW</td><td colspan="2">114.0 GW</td></tr>
<tr><td rowspan="2">Existing Electrolysis Projects</td><td>ANNOUNCED</td><td>FINANCED</td><td colspan="2">OPERATIONAL</td></tr>
<tr><td>24</td><td>5</td><td colspan="2">0</td></tr>
<tr><td rowspan="6">Top 5 Hydrogen Supply Projects</td><td>DEVELOPER</td><td>PROJECT NAME(S)</td><td>ESTIMATED HYDROGEN OUTPUT (metric tons/year)</td><td>INTENDED USE SECTOR</td></tr>
<tr><td>POSCO Holdings, ONGC Ltd, Greenko ZeroC ltd.</td><td>Greenko Kakinada Hydrogen Phase 1</td><td>176,000</td><td>Industry—ammonia export, Transport—heavy commercial vehicle</td></tr>
<tr><td>Acme Group, IHI Corp.</td><td>ACME GIP Phase 1</td><td>70,400</td><td>Industry—ammonia export</td></tr>
<tr><td>Greenko ZeroC Ltd</td><td>Greenko ZeroC Una Project</td><td>19,272</td><td>Industry—ammonia</td></tr>
<tr><td>JSW Energy Ltd</td><td>JSW Karnataka Hydrogen</td><td>3,800</td><td>Industry—steel</td></tr>
<tr><td>Indian Oil Corp Ltd.</td><td>IOC Panipat Hydrogen</td><td>1,869</td><td>Industry—refining</td></tr>
</table>

Source: Data from BloombergNEF (2023), Ministry of New and Renewable Energy India.
Note: GW = gigawatt; PV = photovoltaic.

National hydrogen demand

- 6 million tons of gray hydrogen is consumed annually in India, 99 percent of which is utilized in petroleum refining and the manufacturing of ammonia for fertilizers.[a]
- 45 percent of expected hydrogen demand by 2030 (about 11 million tons) is likely to be green hydrogen for use by the industrial sector.[b]
- In the long term, domestic hydrogen demand could increase more than four times by 2050, equal to some 29 million tons, largely driven by steel and heavy-duty trucking (RMI).[c]

Export potential

- India has several ongoing conversations and at least one signed bilateral conversations/agreements:
  - Memorandum of understanding (MOU) between India and the Arab Republic of Egypt to set up a green hydrogen plant, $8 billion[d]
  - MOU between India and Singapore for exporting renewable energy and green hydrogen/ammonia from India, starting by 2025[e]
  - India and Australia agreement on migration and the Green Hydrogen Task Force[f]
  - Germany and India agreement of cooperation to export green hydrogen from India to Germany[g]

Government Support Mechanisms

- Transmission wheeling charges waived for green hydrogen projects set up by the end of 2030. Policy to be applicable for 25 years.
- $153 million allocated to fund green hydrogen pilot projects in steel production, shipping, transport, up to 2026, and the development of hydrogen hubs in four states.
- Federal subsidies of a maximum of 50 rupees ($0.60), 40 ($0.48) and 30 ($0.36) per kilogram of hydrogen produced for three successive years.

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4 Project-Level Considerations

TECHNICAL, ECONOMIC, REGULATORY, ENVIRONMENTAL

Hydrogen projects encompass a wide range of considerations at various levels, spanning from technical and economic aspects to regulatory and environmental factors. Here are some key considerations:

Technical Considerations

- *Technology Selection:* Choosing the most suitable hydrogen production, storage, and utilization technologies based on factors such as resource availability, scale of operation, and end use requirements
- *Infrastructure Requirements:* Assessing the infrastructure needs for hydrogen production, transportation, storage, and distribution, including pipelines, refueling stations, and storage facilities
- *Efficiency and Reliability:* Ensuring the efficiency and reliability of hydrogen production processes to maximize energy conversion and minimize downtime
- *Integration with Renewable Energy:* Integrating hydrogen production with renewable energy sources such as wind, solar, and hydroelectric power to produce green hydrogen and reduce carbon emissions

Economic Considerations

- *Cost-Benefit Analysis:* Conducting thorough cost-benefit analyses evaluation of the financial viability of hydrogen projects, considering factors such as capital investment, operational costs, and potential revenue streams
- *Financing and Investment:* Securing financing and investment for hydrogen projects through public and private sources, including government grants, subsidies, venture capital, and project finance

- *Market Demand and Pricing:* Assessing market demand for hydrogen and hydrogen-based products, as well as pricing dynamics, to identify profitable market opportunities and optimize revenue generation

Regulatory Considerations

- *Policy and Regulation:* Understanding the regulatory landscape governing hydrogen production, distribution, and use, including policies related to renewable energy incentives, carbon pricing, safety standards, and environmental regulations
- *Permitting and Licensing:* Obtaining necessary permits, licenses, and approvals from regulatory authorities for hydrogen project development, construction, and operation, ensuring compliance with legal requirements and environmental standards.
- *Stakeholder Engagement:* Engaging with stakeholders, including government agencies, local communities, industry associations, and environmental organizations, to address concerns, build consensus, and garner support for hydrogen projects

Environmental Considerations

- *Carbon Footprint:* Assessing the environmental impact of hydrogen production methods, including greenhouse gas emissions, water consumption, and land use, to prioritize low-carbon and sustainable production pathways
- *Lifecycle Analysis:* Conducting life-cycle assessments to evaluate the overall environmental footprint of hydrogen projects, considering factors such as raw material extraction, manufacturing, transportation, and end-of-life disposal
- *Environmental Mitigation:* Implementing measures to mitigate environmental risks and minimize negative impacts, such as carbon capture and storage, wastewater treatment, and ecosystem restoration

Overall, hydrogen and hydrogen derivative projects require comprehensive planning and analysis across technical, economic, regulatory, and environmental dimensions to ensure successful implementation and maximize their contribution to a sustainable energy future.

PROJECT FUNDING SOURCES

Funding for hydrogen projects comes from various sources, including public, private, and blended finance mechanisms. In addition to direct project financing, governments can stimulate green hydrogen economic activities through tax incentives, project grants, and subsidies **(table 4.1)**.

PROJECT DEVELOPMENT STRUCTURES

Split merchant structure: In the split merchant structure, the entity generating renewable electricity for the electrolyzer operation is distinct from the owner of hydrogen/ammonia production and export facilities. Typically, the project developer owns the hydrogen/ammonia production and export facilities, procuring renewable energy from third parties through medium- to long-term power purchase agreements (PPAs). This arrangement enables separate financing for renewable assets and hydrogen assets, leveraging the expertise of specialized renewable energy developers. In certain instances, the renewable electricity supplier also serves as the purchaser of the green hydrogen produced.

Examples

- A supplier of industrial gases, *Air Liquide,* signed a PPA with Norwegian state-owned company Statkraft to buy 20 megawatts of renewable power from Statkraft's onshore wind farm over three years. The renewable energy will power Air Liquide's electrolyzer plant in Oberhausen, Germany, to produce green hydrogen at an industrial scale for industry and transport applications.[70]

TABLE 4.1

Sources of Funding with Examples

Funding Source	Description	Example
Government grants and subsidies	• Public funding programs: Governments may provide grants, subsidies, or financial incentives to support research, development, demonstration, and deployment of hydrogen technologies. These programs aim to stimulate innovation, drive down costs, and accelerate the transition to a hydrogen economy • Energy and climate funds: Governments may allocate funds from energy or climate-related budgets to support hydrogen projects as part of broader decarbonization efforts. These funds may target specific sectors, technologies, or regions to address strategic priorities and policy objectives.	US Department of Energy, Inflation Reduction Act European Commission, H2FUTURE project CORFO (Corporación de Fomento de la Producción de Chile): $10 million to ENGIE green hydrogen project to fuel Enaex green ammonia plant. Export and credit agencies: EKN, JBIC, Hermes, SACE, US Ex-Im
Public-private partnerships (PPPs)	• Collaborative initiatives: Public-private partnerships bring together government agencies, industry stakeholders, research institutions, and financial institutions to jointly fund and develop hydrogen projects. PPPs leverage the expertise, resources, and networks of multiple partners to address common challenges and achieve shared goals. • Co-investment models: PPPs may involve co-investment agreements where public and private partners share project costs, risks, and rewards. Co-investment models align incentives, facilitate knowledge transfer, and leverage complementary strengths to maximize project impact and value creation.	A collaboration involving the Chilean government and private sector leaders like ACWA Power, CWP Renewables, Envision, Iberdrola, Ørsted, Snam, and Yara. The Green Hydrogen Catapult aims to rapidly scale up the production of green hydrogen to drive down costs and accelerate the global hydrogen economy. A partnership between the Namibian government and Hyphen Hydrogen Energy, a private company. The initiative involves co-investment in green hydrogen production facilities, with plans to produce and export green hydrogen to international markets.

Funding Source	Description	Example
Project finance	• Debt financing: Hydrogen projects may raise capital through project finance arrangements, where lenders provide loans or debt instruments secured by project cash flows and assets. Debt financing offers long-term funding with fixed or variable interest rates and may involve syndicated loans, bonds, or other debt instruments. • Equity financing: Hydrogen projects may attract equity investment from investors, including institutional investors, private equity firms, venture capitalists, and corporate investors. Equity financing provides capital in exchange for ownership stakes in the project, offering potential returns through dividends, capital gains, or exit strategies.	The Hydrogen Valley project in South Africa aims to create a hydrogen corridor linking various hydrogen production, storage, and utilization sites across the country. The project involves co-investment from the South African government, private companies (such as Anglo American and Bambili Energy), and international financial institutions. The financing structure includes grants, equity investment, and debt financing.
Venture capital and start-up funding	• Venture capital: Start-ups and early-stage companies developing innovative hydrogen technologies may raise capital from venture capital firms, angel investors, or corporate venture funds. Venture capital funding supports technology development, market validation, and business expansion, often in exchange for equity ownership. • Accelerator programs: Accelerators and incubators provide funding, mentorship, and resources to early-stage hydrogen start-ups, helping them refine business models, develop prototypes, and scale operations. Accelerator programs offer access to networks, expertise, and funding opportunities to support entrepreneurial ventures.	Several project types focusing on technology and market development. Examples: • Enapter, a green hydrogen start-up based in Thailand, develops modular electrolyzers for hydrogen production. • Hyundai Motor Group H2 Ventures, a corporate venture capital fund dedicated to investing in hydrogen start-ups globally. • Hive Hydrogen, a South African start-up focusing on producing green hydrogen and ammonia for domestic use and export.

Funding Source	Description	Example
International finance institutions	• MDBs, such as the World Bank and IFC, Asian Development Bank, and European Investment Bank provide financing, technical assistance, and policy support for hydrogen projects in developing countries. MDBs offer concessional loans, grants, guarantees, and technical assistance to promote sustainable development, climate action, and infrastructure investment. The IFC also provides "upstream" early project development support for investment rights. • Regional development banks, such as the Inter-American Development Bank and African Development Bank, provide financing and technical assistance for hydrogen projects in specific regions or subregions. Regional banks support economic integration, social inclusion, and environmental sustainability through targeted investments and capacity-building initiatives.	IFC Blended Finance, Green Climate Fund, Climate Investment Fund, KfW, European Investment Bank. The IFC and Green Climate Fund partnership, 2023, blended concessional financing to support RenewStable Barbados, a 50 megawatt solar generation facility with green hydrogen and lithium-ion battery storage (see *Case Study 5: RenewStable Barbados*).
Corporate partnerships and strategic alliances	• Carbon credits: Hydrogen projects may generate carbon credits or offsets through emissions reductions or carbon sequestration activities. Carbon credits represent the environmental benefits of reducing greenhouse gas emissions, which can be traded or sold in carbon markets to generate revenue or finance project costs.	The EU Emissions Trading System, the world's largest carbon market, includes mechanisms that support green hydrogen production through emissions trading and offset credits.

Source: Original figure for this publication.
Note: MDBs = Multilateral development banks.

BOX 4.1

Case Study 5

RenewStable Barbados

IFC has partnered with the Green Climate Fund (GCF), HDF Energy, Rubis, and IDB Invest to develop a green hydrogen project in Barbados, known as the RenewStable Barbados project. This initiative is set to be a 50-megawatt solar generation facility that integrates green hydrogen and lithium-ion battery storage to provide continuous and clean electricity to the Barbadian grid.

In October 2023, the GCF Board approved an IFC-cofinanced project, allocating up to $40 million in blended concessional financing and $1 million in technical assistance for RenewStable Barbados. The project represents the first instance of GCF supporting an IFC investment with concessional financing, the first green hydrogen project for IFC, and the first green hydrogen project in the Latin America and Caribbean region. It aims to significantly mitigate greenhouse gas emissions, avoiding 693,000 tons of CO_2 over its lifetime, while reducing Barbados' reliance on costly fuel imports.[a]

IFC's upstream engagement in RenewStable Barbados demonstrates its commitment to advancing sustainable development through early-stage project support. IFC played a crucial project development role by conducting solar resource assessments, geotechnical and hydrological studies, and environmental life-cycle assessments, which were pivotal in strengthening the project's bankability and attracting international investors.[b] By collaborating with partners such as GCF, IDB Invest, HDF Energy, and Rubis, IFC provided both financial and technical assistance to mitigate risks and ensure the project's feasibility.[c] Additionally, IFC's involvement in early-stage development and capacity-building efforts, such as supporting the Environmental and Social Impact Assessment, highlighted its strategy to create market conditions favorable for private sector investment.[d] This comprehensive approach addresses the financial and technical challenges, demonstrating how upstream engagement can drive successful and sustainable projects.

RenewStable Barbados is particularly unique as it aims to provide a continuous and clean energy supply to an island nation vulnerable to climate change–induced natural disasters and currently dependent on imported fossil fuels. By integrating green hydrogen technology and solar energy, the project will enhance the nation's energy resilience and food security, while advancing Barbados' ambitious goal of achieving 100 percent renewable energy by 2030.[e]

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- Global multi-energy company TotalEnergies signed a memorandum of understanding with Air Liquide for the long-term supply of 15,000 tons of green and low-carbon hydrogen per annum to the TotalEnergies refining and petrochemical platform in Normandy, France. TotalEnergies will supply approximately 700 gigawatt-hours of renewable electricity per year to power 50 percent of Air Liquide's 200-megawatt Normand'hy electrolyzer, corresponding to the share of hydrogen delivered by Air Liquide to TotalEnergies' refinery in Normandy.[71]

INTEGRATED STRUCTURE: In an integrated structure, all stages of the production process, from renewable energy generation to hydrogen production and potentially downstream processes such as conversion, storage, and distribution, are managed by a single entity or consortium. This approach seeks to streamline operations, optimize efficiency, and potentially reduce costs by integrating various components of the hydrogen value chain. The integrated structure allows for tighter coordination between different stages of production, ensuring a seamless transition and optimal utilization of resources throughout the process. Additionally, it may facilitate greater control over the quality and reliability of hydrogen production and enable innovation and customization to meet specific market needs.

Examples

- *Hydrogen Infrastructure Projects:* Large-scale hydrogen infrastructure projects, such as those aiming to establish hydrogen hubs or export corridors, often adopt an integrated structure. These projects involve coordination between government agencies, energy companies, infrastructure developers, and technology providers to establish a comprehensive hydrogen ecosystem.
- *Hydrogen Production Clusters:* In regions with abundant renewable energy resources, integrated hydrogen production clusters can emerge. These clusters may involve collaboration among multiple stakeholders, including renewable energy developers, electrolyzer manufacturers, hydrogen producers, and end-users, to optimize the entire value chain.
- *Hydrogen Refueling Stations:* Companies operating hydrogen refueling stations may integrate renewable energy generation, hydrogen production, and distribution facilities. This integrated approach ensures a consistent and sustainable hydrogen fuel supply for fuel cell vehicles.

MERCHANT/OFFTAKE RISK

The adoption of green hydrogen through offtake agreements has started, but efforts remain at a small scale. Offtake agreements play a critical role in driving project development and financing by facilitating the sale and purchase of hydrogen between producers and buyers **(table 4.2)**. The adoption of green hydrogen through offtake agreements has commenced, albeit at a relatively modest scale. Notably, of the 2 million tons of "low"-emission hydrogen covered by offtake agreements, more than half are characterized as preliminary with nonbinding conditions.[72] The introductory nature underscores the nascent stage of the green hydrogen market and the need for further development. While the existing hydrogen and ammonia prices are derived from title transfer facility gas prices, there is little history of long-term offtake agreements since their markets are typically small and regionalized. This lack of a track record and of market depth means a mature market structure as is now seen in liquidated natural gas flows is still several years away, and substantial support will be needed to de-risk the demand side.

Challenges in securing offtake agreements

Despite the promising trajectory, securing long-term offtake agreements for green hydrogen presents several challenges. Industries, particularly those reliant on legacy processes, face substantial investments in retrofitting infrastructure for hydrogen integration. Moreover, potential buyers exhibit reluctance to commit to long-term agreements, driven by concerns over technology maturity and the anticipation of cost reductions over time. Recent concerns surrounding

TABLE 4.2

Typical Green Hydrogen Offtakers

Buyer	Example
Government Entities	Government agencies at the local, regional, or national level may act as offtakers to support the development of green hydrogen infrastructure or meet sustainability targets in public facilities. Germany's flagship H2Global double auction program is designed to purchase €900 million of ammonia, methanol, and sustainable aviation fuel via up to 10-years fixed price hydrogen offtake agreements from outside the EU and the European Free Trade Association and sell to the domestic market through short-term contracts (typically one year) at the highest sale price resulting from the auction.
Industrial Manufacturers	Industries with high energy requirements, such as steel, chemicals, and refining, may utilize green hydrogen as a feedstock or fuel for their processes.
Transportation Sector	Companies operating fleets of vehicles, including public transit agencies, logistics companies, and vehicle manufacturers, may procure green hydrogen to fuel hydrogen-powered vehicles.
Utilities and Energy Companies	Utilities seeking to diversify their energy portfolios or comply with renewable energy mandates may purchase green hydrogen for power generation or energy storage applications.
Hydrogen Refueling Stations	Operators of hydrogen refueling stations catering to hydrogen fuel cell vehicle users may enter into offtake agreements with hydrogen producers to ensure a reliable supply of hydrogen.
Hydrogen Traders and Brokers	Companies specializing in the trading and brokerage of hydrogen may serve as intermediaries between producers and end-users, facilitating offtake agreements and ensuring market liquidity.

Source: Original figure for this publication.

higher-than-expected green hydrogen prices and supply uncertainties further complicate the negotiation landscape.

Actions to address concerns of potential offtakers
To address the concerns of potential offtakers, stakeholders must prioritize transparency, flexibility, and risk mitigation in offtake agreements. Robust contractual frameworks can provide assurances regarding pricing mechanisms, supply reliability, and technology advancements. Additionally, mechanisms for price adjustment and risk-sharing can enhance the attractiveness of long-term commitments amid market uncertainties.

Key considerations for offtake agreements
Several key considerations underpin the negotiation and implementation of offtake agreements for green hydrogen projects:

- *Offtaker creditworthiness:* Lenders require creditworthy buyers or entities capable of providing suitable credit support, enhancing confidence in project viability.
- *Quality and quantity:* Agreements should specify hydrogen quality standards, quantity requirements, and inspection protocols to ensure compliance and reliability.
- *Take-or-pay provisions:* To secure predictable revenue streams, offtake contracts may include take-or-pay clauses, guaranteeing minimum purchase commitments. In addition, project developers may consider flexible production output targets to accommodate reduced plant availability and reliability and to avoid liquidated damages for underperformance.
- *Price mechanisms:* Flexible pricing structures, such as indexed hydrogen purchase agreements (HPAs), cater to stakeholders' diverse risk profiles and preferences. The most common types of HPAs are either fixed or indexed. In a fixed-price HPA, the buyer agrees to a fixed real price for the entire contract duration, while an indexed HPA is linked to a specific market index, such as inflation.
- *Tenor and termination:* Contractual terms should align with project life cycles, incorporating provisions for the maturity of loans and offtake agreements, as well as specifying termination terms and conditions for early termination and force majeure events.

Offtake agreements serve as foundations in developing and financing green hydrogen projects, providing essential assurances to producers and buyers. Despite prevailing challenges, proactive collaboration and innovative contractual frameworks can mitigate risks and unlock the full potential of green hydrogen as a cornerstone of sustainable energy systems.

5

Conclusions *and* Recommendations

The transition to clean energy is a critical global priority, requiring coordinated efforts and strategic actions among government, business, and sources of innovation. Green hydrogen emerges as a transformative energy carrier with the potential to reform various sectors and drive sustainable development worldwide. As countries seek to accelerate their clean energy transitions, green hydrogen offers a pathway to decarbonize systems, enhance energy security, and promote economic growth. However, green hydrogen costs are currently elevated, may not be suitable for all regions or applications, and should be considered against alternatives based on a comprehensive and balanced framework evaluating economic, technical, environmental, social, and infrastructure conditions.

As has been discussed throughout the report, key recommendations for harnessing the full potential of green hydrogen to advance clean energy transitions include the following: (a) defining the optimal role for green hydrogen in a country's and region's economy; (b) focusing on strategies and policies at the national and global levels to find the optimal technologies, infrastructure, systems, and mechanisms to reduce cost and incentivize sustainable production of green hydrogen; (c) collaborating across borders; and (d) providing de-risking solutions to stimulate demand, to match supply and demand, and ultimately to facilitate the adoption of lower-carbon systems across various sectors of the economy.

Defining the role of hydrogen in clean energy transitions. To effectively integrate hydrogen into a country's clean energy transition, policy makers and stakeholders must recognize its multifaceted role. Beyond decarbonizing hard-to-abate sectors, such as heavy industry and transportation, hydrogen can serve as a versatile energy carrier, enabling grid balancing and energy storage from renewable sources. The first profitable applications will likely emerge around local industrial use of green hydro-gen. Embracing green hydrogen as a key pillar of the transition requires comprehensive strategic planning and alignment with national energy goals.

Stimulating demand and cross-border collaboration. Stimulating demand for green hydrogen and its derivatives necessitates proactive measures to incentivize adoption across industries and to foster cross-border trade and collaboration. Establishing harmonized regulatory frameworks, standards, and certification programs can facilitate the seamless flow of green hydrogen across borders, promoting regional integration and market growth. Moreover, targeted initiatives, such as joint research and development projects and knowledge-sharing platforms, can accelerate technology innovation and market expansion.

Building strategies for optimal country fit. Tailoring green hydrogen strategies to fit each country's unique context is imperative for maximizing impact and ensuring long-term sustainability. Countries can position themselves as leaders in the global hydrogen economy by identifying priority sectors with high potential for hydrogen utilization, optimizing value chain integration, and leveraging comparative advantages in international trade. Strategic partnerships and alliances can further enhance competitiveness and resilience, fostering collaboration along the entire hydrogen value chain.

Reducing electrolyzer costs. Reducing electrolyzer costs is crucial to securing the widespread adoption of green hydrogen as a clean energy carrier. Lowering these costs can significantly enhance the economic viability of hydrogen production, making it more competitive with traditional fuels. This can be achieved through technological advancements, economies of scale, increased electrolyzer efficiency, and increased manufacturing efficiency. As costs decrease, green hydrogen becomes a more attractive option for various sectors, accelerating the transition to a sustainable energy system and supporting global decarbonization goals. Implementing supportive policies and fostering innovation will be key to driving these cost reductions.

Designing hydrogen infrastructure for accessibility and efficiency. Designing robust hydrogen infrastructure is essential for unlocking its full potential and ensuring widespread accessibility. Colocating production facilities with demand centers and investing in efficient distribution networks can minimize transportation costs and enhance supply chain resilience. Additionally, exploring innovative solutions for hydrogen storage and shipping, such as liquefaction and ammonia-based carriers, can enable cost-effective delivery to distant markets and remote regions.

Supporting project development and technology deployment. Supporting project development requires a holistic approach that combines technological innovation, policy support, and financial incentives. Providing access to best-in-class technologies, process optimization tools, and regulatory frameworks can accelerate the deployment of existing production methods and catalyze the development of next-generation hydrogen projects. Moreover, fostering collaboration between industry stakeholders, research institutions, and government agencies can streamline project financing and mitigate investment risks.

Ensuring adequate availability of capital and financial support. Ensuring adequate availability of capital is paramount for scaling up hydrogen infrastructure and fostering market growth. Governments can play a crucial role in mobilizing public and private investment through targeted incentives, grants, and concessional financing mechanisms to make green hydrogen cost-competitive with gray hydrogen. Public-private partnerships and blended finance models can leverage public funds to attract private investment and de-risk projects, particularly in early-stage and high-risk ventures. Moreover, promoting transparency and accountability in project financing and governance structures can enhance investor confidence and facilitate long-term sustainability.

Enacting supportive policies, incentives, and regulations. Enacting supportive policies, incentives, and regulations is essential for creating an enabling environment for green hydrogen deployment and market development. Implementing carbon pricing mechanisms, tax incentives, and feed-in tariffs can incentivize investment in green hydrogen technologies and level the playing field with conventional fuels. Moreover, establishing clear regulatory frameworks, safety standards, and permitting processes can provide certainty and clarity to industry stakeholders, fostering trust and confidence in the market.

In conclusion, integrating hydrogen into clean energy transitions holds immense promise for addressing the dual challenges of climate change and energy sustainability. By embracing hydrogen as a cornerstone of their energy strategies, countries can unlock new pathways to prosperity, innovation, and resilience in the face of global challenges. The recommendations outlined in this section offer a road map for policy makers, industry stakeholders, and civil society actors to seize the opportunities presented by green hydrogen and accelerate progress toward a cleaner, more sustainable energy future. Through strategic collaboration, innovative solutions, and bold policy action, the world can chart a course toward a world powered by green hydrogen, where clean energy is not just a vision but a reality for future generations.

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