A Global Hydrogen Future

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A Joint Message from **Ernest Moniz**, President and CEO of EFI, and **Fahad Alajlan**, President of KAPSARC

A Call to Action

Hydrogen is a significant part of energy conversations because of its scalability, flexibility, and decarbonization potential. Considerable efforts are underway globally to determine the most effective ways to introduce hydrogen into the energy mix. This report—*A Global Hydrogen Future*—aims to inform this discussion.

Considering decarbonization goals and the vast scale of energy industries, it is evident that there is a burgeoning need to establish a new industry centered on hydrogen as a clean energy carrier. In today's urgent push toward sustainable energy solutions, hydrogen stands out as a potential catalyst for accelerating the transition. Its unparalleled potential lies in its capacity to be generated with low to zero CO_2 emissions[a] from water or fossil fuels (with carbon capture and sequestration) and to serve many end-uses. Rapid and large-scale escalation of this new industry is imperative to fully realize the potential of hydrogen and integrate it as a strategic component of achieving net-zero emissions goals.

Given the success of past partnerships, the Energy Futures Initiative (EFI) and the King Abdullah Petroleum Studies and Research Center (KAPSARC) established a research collaboration motivated by a shared desire to accelerate the clean energy transition on a global scale. This joint study brings together two complementary perspectives—the United States and Saudi Arabia—two leaders in global energy markets, and two nations with significant natural resources that can create opportunities to develop hydrogen at scale.

This research program has focused on the development of a global hydrogen market. In-person workshops were held in Washington, D.C., and Dubai, UAE, complemented by two virtual workshops. These publicly available analyses and their associated workshops, white papers, and reports will provide a foundation for Saudi Arabia to play an even greater leadership role in the clean energy transition in the Middle East and North Africa (MENA) and globally. This work has initiated analytical collaborations focused on other decarbonization issues, including carbon capture, utilization, and storage (CCUS), and system modeling options and opportunities. This builds on a history of close cooperation between KAPSARC and EFI. ■

a Hydrogen production can have negative emissions when carbon dioxide is captured and stored, removing captured carbon from the natural carbon cycle.

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Executive Summary, Key Findings, and Recommendations

The need for a global clean hydrogen market that lowers costs, increases energy security, and supports decarbonization efforts is emerging as a key issue in decarbonization plans worldwide. The clean hydrogen market is still in its infancy, and development is needed along the entire supply chain.

> **To increase current production of low-carbon hydrogen (1 MMtpa) to hundreds of MMtpa by 2050 a first important step will be to replace fossil fuel based hydrogen with low-carbon hydrogen production.**

According to the International Energy Forum, low-carbon hydrogen production and utilization must increase from about 1 million metric tons per annum (MMtpa) today to hundreds of MMtpa by 2050 to meet growing energy demands during the energy transition. An important step will be to replace hydrogen made by unabated fossil fuels with low-carbon hydrogen for existing end-uses (mostly in refining and ammonia for fertilizers).[1] Market growth will involve expansion and development in production, transportation, storage, and end-use. Scaling up hydrogen will require new business models, pricing, contracts, regulations, standards, certificates, and policies.[2]

Hydrogen has become very topical, both among countries and industries, and significant efforts are underway to determine the most effective ways to introduce hydrogen into the energy mix. This report aims to inform policymakers and other stakeholders. Hydrogen is framed as a viable solution to the urgent need to address climate change and net-zero emissions by 2050. As part of this framing, a potential role for hydrogen in industrial decarbonization has been highlighted because of its promise as a versatile, clean, and scalable solution. This report also touches on the methods of hydrogen production and hydrogen's potential as a substitute for natural gas.

Theoretically, every country with a supply of water can produce green hydrogen, but not every nation can produce every clean hydrogen pathway (e.g., a natural gas supply is needed to produce blue hydrogen). Countries and regions can be categorized as global producers, consumers, or self-sufficient in hydrogen production. In general, the United States, Canada, Australia, and the Middle East and North Africa (MENA) region, with abundant natural gas resources and substantial clean and renewable energy capacity, could emerge as global producers and exporters of clean hydrogen. Whether countries look to meet or create new domestic demand first remains to be seen, but some countries may seek to meet domestic demands first and eventually foster new global markets with enough production for exports. Europe and East Asia, facing constraints on renewable energy development and natural gas resources, could become major hydrogen importers. In the end, use doesn't depend on the "color" of hydrogen, but the life cycles of greenhouse gas (GHG)[b] emissions do.

Currently, hydrogen is not traded as a global commodity, leading to opaque pricing regimes that are contingent on demand volumes and isolated regional markets or bilateral agreements. Shipping and transport costs further affect the overall cost competitiveness of clean hydrogen, making it more expensive compared with fossil fuels like natural gas. To be successful, clean hydrogen must become cost-competitive with alternative clean energy pathways.

Despite these challenges, there have been substantial commitments to investment in clean hydrogen projects globally. This report generally uses the term "clean hydrogen"—unless otherwise noted by a specific policy definition—to refer to these forms of hydrogen produced with negative, near-, and low- to zero-carbon emissions. As of May 2024, more than 1572 projects had been announced, as had nearly $680 billion in direct investments through 2030, with approximately $75 billion reaching the final investment decision (FID) stage.

These projects aim to produce hydrogen predominantly from water through electrolysis powered by renewables (green hydrogen), by nuclear energy (red, pink, purple hydrogen), from methane through steam reforming (SMR) with carbon capture, utilization, and storage (CCUS) (blue hydrogen), or from pyrolysis[3] (turquoise hydrogen)[c]. There is active interest in geologic hydrogen (white hydrogen). This report focuses on green and blue hydrogen since these supply pathways are relatively more developed. ■

b Greenhouse gas emissions are gases that trap heat in the atmosphere (carbon dioxide, methane, nitrous oxide, and fluorinated gasses). For more information: https://www.epa.gov/ghgemissions/overview-greenhouse-gases.

c For a full description of the colors defining the methods of hydrogen production, please reference Figure 1.

Focus Areas

This report and associated analysis is structured around three main focus areas: **Opportunities for Hydrogen Demand, National Policies and International Regulations**, and **Hydrogen Market and Price Formation.**

The **Opportunities for Hydrogen Demand chapter** highlights the potential for global hydrogen demand by reframing hydrogen as an energy carrier and emphasizing its role in existing energy systems or where the opportunity for growth exists with the right combination of policy and market factors.

> **Overall, hydrogen presents substantial opportunities for both decarbonization and energy system flexibility, positioning it as an important player in the transition to a low-carbon economy.**

Overall, hydrogen presents substantial opportunities for both decarbonization and energy system flexibility, positioning it as an important player in the transition to a low-carbon economy. Decarbonizing traditional hydrogen applications presents a near-term opportunity, but costs of production and end-price barriers remain. Policy incentives and new regulations are crucial for the widespread transition of power and transportation systems. Policy support also is necessary for making hydrogen pathways economically competitive.

Despite its lower overall intensity compared with conventional fossil fuel-based pathways, clean hydrogen production's water consumption should account for the potential water displaced in regions of the world experiencing water scarcity. More will be known on this issue once projects are operating and technology progresses. Also, research indicates the green hydrogen electrolysis process requires less water consumption than earlier reports indicated.[4]

Hydrogen's role in various industries is evolving rapidly to address emissions reduction and sustainability goals. For example, in the steel industry, there's a shift toward direct reduced iron-electric arc furnace processes, particularly in regions with abundant natural gas, like North America and the Middle East. Initiatives in Europe and Japan emphasize green steel production, with projects targeting significantly reduced emissions. While hydrogen's role in traditional blast furnace/basic oxygen furnace processes is nascent, trials indicate the potential for long-term adoption. Based on discussions with key stakeholders along the hydrogen value chain, this chapter details the primary technical considerations that developers face today as they try to scale up hydrogen operations. This overview of demand opportunities considers regional variations to assess the best near-term opportunities.

This section also highlights the potential role of hydrogen derivatives (e.g., ammonia, methanol) in energy transport and international trade. In shipping and maritime applications, hydrogen is showing promise as a direct fuel or derivative supporting decarbonization efforts. Similarly, in aviation and heavy-duty transportation, hydrogen can contribute to sustainable aviation fuels (SAFs), synthesis fuels and e-fuels as drop-in replacements, as well as other emissions reduction strategies. Challenges remain, including infrastructure scalability and water availability for electrolysis-based hydrogen production. On the other hand, natural gas is unavailable at scale in most regions, so blue hydrogen is likely to be a significant industry in limited locations (including the United States and MENA).

Additionally, hydrogen can serve as a crucial component in long-duration energy storage for renewable energy and for enhancing grid resiliency. Its potential extends to high-grade industrial heating applications, such as cement, glass, ceramic, and steel production, although cost considerations and technological viability are important factors.

Despite challenges, investments exceeding $570 billion by 2030 underscore hydrogen's significance in achieving net-zero emissions goals. Hydrogen presents a promising pathway for emissions reduction and a sustainable energy transition across multiple sectors, paving the way for a cleaner and more resilient future.

> **Standardization, regulatory certainty, and public-private partnerships are key factors for market growth.**

The **National Policies and International Regulations chapter** emphasizes the importance of national policies and international regulations in spurring a global hydrogen market. Bottom-up project developments, combined with top-down strategies and policy mechanisms, are essential for rapid scalability. Standardization, regulatory certainty, and public-private partnerships are key factors for market growth.

The analysis discusses the global outlook for hydrogen production and its potential as an energy commodity. It highlights the growing investment in hydrogen production, particularly in regions like MENA, Asia, Australia, and Europe. Countries like Saudi Arabia, Egypt, Morocco, the United Arab Emirates, and Oman are investing heavily in ammonia and hydrogen production, with MENA and Asia forecast to lead in hydrogen capacity by 2030-2035.

Hydrogen production is expected to increase significantly by 2035, with Asia projected to produce hydrogen through large hubs in China and India. Singapore also has a national plan to become a catalyst for global hydrogen trade.[5] The Chinese central government aims to use renewable feedstock resources to produce 100,000 to 200,000 tons of green hydrogen by 2025.[6] Challenges include uneven project maturity globally and the need for realistic cost expectations. Public-private partnerships could help overcome challenges, with sovereign wealth funds playing a significant role, as seen in initiatives like SDG Namibia One.

With the need for coalescence around international regulations, establishing carbon pricing and subsidies are seen as potential catalysts for global hydrogen market development. Certification schemes for carbon intensity are crucial for establishing standards, though challenges like variable acceptability of hydrogen sourcing remain. Midstream transportation challenges—such as liquefaction energy inputs and storage issues—must be addressed for a global hydrogen market to develop. As demonstrated by Saudi Arabia's NEOM project, both public-sector support and private-sector financial backing and guarantees are crucial.

> **Overall, the analysis emphasizes the potential of hydrogen as a clean energy solution while addressing the challenges and policy frameworks necessary for its widespread adoption.**

Beyond replacing production methods, which are using unabated fossil fuels for established end-uses, the industry could focus on a complementary role for hydrogen with electrification efforts in storing renewable energy and decarbonizing fuel-based applications such as high-heat industrial and transportation uses. Overall, the analysis emphasizes the potential of hydrogen as a clean energy solution while addressing the challenges and policy frameworks necessary for its widespread adoption.

The discussion maintains that pricing mechanisms must balance producer and consumer interests while insulating against volatility.

The Hydrogen Market and Price Formation chapter analyzes the challenges of balancing pricing mechanisms and the possible development of a hydrogen economy. The discussion maintains that pricing mechanisms must balance producer and consumer interests while insulating against volatility. Transparent pricing is paramount in the hydrogen market because it fosters trust and facilitates efficient transactions. Also explored is the idea that traditional oil and gas producers are well positioned to lead hydrogen production, particularly in the MENA region. Long-term offtake agreements, infrastructure development, and government incentives are critical for market viability.

The hydrogen market is in its initial stages and requires coordinated efforts from industry stakeholders and policymakers to overcome barriers and realize its full potential as a sustainable energy solution. Clear policy frameworks, financial incentives, and strategic partnerships will be instrumental in driving the growth of the hydrogen economy.

The report findings ask policymakers to focus on the highest-value uses of hydrogen, in the context of decarbonization efforts, and provide insights into the formation of hydrogen markets, drawing parallels with the historical practices and challenges that influenced the natural gas industry and its associated market development. It highlights the evolution of liquefied natural gas (LNG) business models from tightly integrated value chains to more flexible structures, driven by market pressures and government regulations. Additional analysis focuses on the uncertainty surrounding future hydrogen pricing and costs, comparing it to past fluctuations in oil and gas markets and acknowledging the long development path of these markets.

Additionally, there is an examination of the shift in corporate strategies toward renewable energy sources and biofuels, as well as on CCUS. These shifts are driven by government-led policy initiatives, regulations, and shareholder demands for profitability as well as by corporate environmental, social, and governance reporting requirements. The conclusion emphasizes the importance of allowing companies to develop low-carbon hydrogen value chains through negotiated deals, acknowledging the nascent nature of the low-carbon hydrogen industry.

Lastly, there is an emphasis on the need for continued government support and industry collaboration to navigate uncertainties and challenges, so that viable and sustainable routes for clean hydrogen technology can be achieved.

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By implementing these recommendations, governments can play a crucial role in fostering the development of a robust and sustainable hydrogen economy, ensuring market stability, investment certainty, and alignment with climate goals.

Conclusions

Given the nascent stage of development of a global clean hydrogen market, the report provides:

- A framework for understanding the factors that can play a crucial role in fostering the growth of a hydrogen economy.
- Recommendations for decision-makers to clarify and support pathways for hydrogen in the global energy mix.

By implementing these recommendations, governments can help foster the development of a robust and sustainable hydrogen economy, ensuring market stability, investment certainty, and alignment with climate goals.

Opportunities for Hydrogen Demand

- **Policy framework development:** Formulate comprehensive policies that support the transition of hydrogen from a chemical commodity to a key energy carrier and to dedicated demand incentivization programs.
- **Diversified utilization of clean hydrogen:** Encourage the utilization of clean hydrogen in various industries and technologies to increase demand and secure a larger share of energy production. Accompanying this is a possible role for international and national oil companies to be incentivized to leverage experience, upgrade capacities, train workforces, and enable technologies like CCUS (for facilitating blue hydrogen production) to take off.

National Policies and International Regulations

- **Synergistic approaches:** Encourage a combination of bottom-up project (project-led) developments driven by market forces and top-down (government-led) strategies supported by policy mechanisms.
- **Establish methodologies for regulatory certainty:** Through an ISO-like organization establish uniform definition criteria for hydrogen and for life cycle GHG emissions.
- **Aspirational vs. probable:** Using information from the database created as part of the project, of the more than 1,400 low-carbon hydrogen projects announced globally, only 95 are likely to come to market in the 2030-2035 time frame.

Hydrogen Market and Price Formation

- **Equitable hydrogen pricing mechanisms:** Develop hydrogen pricing mechanisms that ensure transparency of hydrogen price reporting that will enable better market formation and mitigate volatility risks and instill confidence in project returns in the nascent but rapidly growing market.
- **Market formation:** Understanding the global framework and some of the historical practices that have influenced the natural gas industry, and the development of an associated market, can give valuable insights into the formation of a hydrogen market.

Chapter 1: Introduction and Framing

What Sets This Report Apart?

Hydrogen Market and Price Formation

In a world where abundant, affordable, and sustainable sources of clean energy are needed to meet the global commitment to combat climate change, market forces and competition must be considered, which is why a review of the development of natural gas markets is instructive.

In examining the hydrogen value chain and different phases of activity regarding market development and maturity—specifically, investment, construction, and exploitation—this paper explores the current state of play for green hydrogen and analyzes it within the historical context of the development of the natural gas markets to provide a comparative analysis.

Even though the liquefied natural gas (LNG) market is presented as a possible model for global hydrogen market development, it's important to understand that the LNG market is also still forming and is not truly liquid. This is significant because the global LNG market has taken decades to develop to where it exists currently. Our simple definition of a global commodity market is one in which derivative financial products can be created and values derived from the underlying commodity. This is significant as investment vehicles allow for more liquidity in the sector.

Identify Current Gaps in Policy, Regulation, and Movement in the New Hydrogen Economy

This report intends to provide a comprehensive assessment of the challenges and opportunities for global hydrogen development. It offers recommendations to the international policy, regulatory, and economic communities on how to bolster global hydrogen development in the coming decade. Importantly, these guiding principles draw upon bottom-up insights gleaned from the EFI-KAPSARC joint work program's Global Hydrogen Database. This analysis highlighted 95 clean hydrogen projects globally that represent the most likely opportunities for near-term development of clean hydrogen demand from nontraditional uses (i.e., not for refining or for fertilizer) in 2030-2035.

While many modeling scenarios consider global hydrogen market formation on the 2030 and 2050 timescales, this report's evaluation of project criteria yielded a filtered database of projects that can serve as a foundation for predictive models and scenario analyses, offered a signpost for where the market is going, and highlighted midterm pathways for hydrogen commercialization.

In addition to this bottom-up approach at the project level, the report provides a top-down analysis of global policy and regulatory trends, challenges, and opportunities informed by a literature review, white papers on price formation and industrial decarbonization, and two regional convenings of industry stakeholders. Combined, these approaches provide a holistic perspective to guide international institutions, national governments, and multinational corporations in developing hydrogen markets in the near term across the globe.

Why Hydrogen?

Globally, climate change continues to be one of the most substantive policy challenges, given the major impacts on societies and the frequency and intensity of catastrophic weather events that threaten human health, safety, and economic well-being. The United Nations Environment Programme's Intergovernmental Panel on Climate Change has shown that, to avoid even more severe impacts, the global economy must reach net-zero emissions by 2050.[7,8] The clean energy transition will require an unprecedented scale of investment and technological innovation to reduce greenhouse gas (GHG) emissions, mitigate environmental and human harms, and ensure energy security for countries across the globe.

Governments and industries are investing large amounts of capital to expand and proliferate low-carbon energy technologies to address energy security and environmental sustainability concerns simultaneously. In 2022, a record $1.1 trillion was invested in low-carbon technologies, reaching parity with investments in fossil fuel for the first time in history, an indication that the paradigm is shifting.[9,10] Renewable energy investment has grown 17% since 2021, with $495 billion invested in 2022. Also, in 2022 $466 billion was invested in electric vehicles and related infrastructure such as charging stations and networks, a rise of 54%. Nevertheless, global demand for fossil fuels reached an all-time high in 2023.[11]

Currently, electrification is the most expedient and economic way to offset the majority of fossil fuel emissions and is expected to rise from 20% of total final energy consumption today to over 50% by 2050.[12] To achieve net-zero emissions, this electrification—which is predominantly used today in buildings, transport, and certain industrial applications—could be paired with a clean fuel to decarbonize other sectors. Low- and zero-carbon fuels can facilitate deep decarbonization in industries that are particularly difficult or expensive to electrify, such as shipping, aviation, and high-heat industrial processes. Clean hydrogen as a fuel source can fill this role. Clean hydrogen is versatile as an energy carrier, flexible in supporting decarbonization in existing industries, and scalable, creating new energy pathways across economic sectors.

Hydrogen, when combusted or used in a fuel cell, produces no carbon emissions.[d] Regarding its versatility, hydrogen can be produced using a variety of methods in different regions of the world, based on the local energy resources available.

Hydrogen production most commonly involves reacting natural gas with steam, known as steam methane reformation. This process is low-cost, scalable, and very emissions-intensive but can reach net-zero emissions when paired with carbon capture and storage. Hydrogen production also can use electricity to split hydrogen atoms from water molecules in a process known as electrolysis. While electrolysis can use zero-carbon power resources (e.g., renewable, nuclear) and produce carbon-free hydrogen, the process is currently costly and in early stages of development and commercialization.

The advantage of using natural gas versus water as the source of hydrogen is that less energy is required to disassociate methane in natural gas. Blue hydrogen production also can leverage existing infrastructure and facilitate a smoother transition from fossil fuels. The disadvantage is that natural gas is less ubiquitous globally and the carbon atom must be managed so as not to release carbon dioxide (CO_2) into the atmosphere. A challenge for the electrolysis of water (green hydrogen) without life cycle CO_2 emissions is the large amount of carbon-free electricity required.

This report uses the term "clean hydrogen" generally, unless otherwise noted by a specific policy definition, to refer to these forms of hydrogen produced with low- to zero-carbon emissions.

While there were only small amounts of initial investment in clean hydrogen in 2022—totaling $1.1 billion—clean hydrogen investment is growing faster than that of any other technology, increasing threefold since 2021.[13] Some estimates suggest clean hydrogen has the potential to reduce

d While hydrogen creates no carbon emissions when combusted, it still produces nitrogen oxide emissions that negatively impact local air quality, particularly in the form of smog or acid rain.

worldwide GHG emissions by approximately 12% to 20% by 2050.[14]

Hydrogen also presents opportunities for investor scalability, with options for both small and large investments as the industry moves up the learning curve. Market outlooks, based on announced policies and projects by governments, estimate the potential value of the hydrogen economy could grow to $1 trillion to $1.4 trillion per year by 2050.[15,16,e]

e These outlooks on the potential value of the hydrogen economy assume policies will be put in place in the near to midterm to achieve global energy system decarbonization.

Given that fossil fuels, delivered for end-use, individually command markets on the trillion-dollar scale, it is at this scale that a new hydrogen industry needs to exist if it is to displace and replace fossil fuel industries for reduced carbon emissions. At this stage, this shouldn't be seen as impossible but rather as a challenge and an indication of the scale needed for hydrogen to become a significant contributor to achieving deep decarbonization.

Hydrogen improves energy system flexibility, given its ability to function as a fuel, specialty chemical, and energy storage medium (Table 1).[17] Today, hydrogen is used predominantly as a specialty

Table 1. Primary applications of hydrogen

Classification	Use Case	Fossil Fuel Displaced	Competing Clean Technologies
Fuel	• Electricity: Combusted in turbines to produce electricity • Process Heating: Used as heat source for high-temperature industrial applications • Transportation: Used in a fuel cell or internal combustion engine) to produce power for electric vehicles	Natural Gas, Coal, Petroleum	• Electricity: Renewable Energy • Process Heating: Direct Electrification • Transportation: Direct Electrification, Biofuels
Specialty Chemical	• Refining: Used as a feedstock to lower the sulfur content of fuels • Chemical Processes: Used to create derivative industrial products and fuels such as ammonia, methanol, liquid organic hydrogen carriers (LOHCs), and synthetic fuels	Natural Gas, Petrochemicals	• Refining: Synthetic fuels • Chemical Processes: Biomass-derived Chemicals, Biological Pathways
Energy Storage Medium	• Grid Balancing: Production of long-term energy storage via excess renewables for use in fuel cells for power applications • Statonary Power: Used as energy source for firm power, backup, and/or peaking capacity • Mobility Applications: Used on and off road as a clean energy carrier for transport, either as hydrogen or other hydrogen carriers (e.g., ammonia, methanol)	Natural Gas, Coal, Petroleum	• Grid Balancing: Long-Duration Batteries • Stationary Power: Pumped Hydropower, Biomass, Nuclear • Mobility Applications: Batteries, Biofuels

Source: EFI, 2024

chemical—acting as a feedstock in refining and chemical processes, such as in fertilizers. As a fuel, hydrogen can produce electricity and support long-haul transportation. It can provide a fuel for high-heat applications in heavy industry and replace fossil fuels in industrial processes. Hydrogen also has the potential as an energy storage medium for grid balancing, stationary, and backup power, and as a carrier for clean energy transport.

Hydrogen presents opportunities for regional decarbonization, especially since green hydrogen production pathways in particular are not limited to specific regions of the world. In some cases, hydrogen production can occur locally and virtually eliminate primary energy shipping costs.

From the production perspective, countries and global regions often fall into three categories: global producers, global consumers, or self-sufficient. The MENA region and Latin America could become global producers given their extensive renewable energy capacity and energy export experience. The MENA region also has low-cost natural gas resources at scale. Leading economies like the United States and China can meet their own demand with domestic supply and potentially create new global hydrogen markets.

The regions with the fewest options for domestic hydrogen production are Europe (e.g., the Netherlands and Germany), East Asia (e.g., Japan and South Korea), and Singapore on behalf of Southeast Asia. These regions lack major natural gas resources and have land constraints on renewable energy development, positioning them to become major hydrogen importers in the future.

Taking these positive characteristics considering hydrogen together, it has the potential to become a major component of a thoughtful and sequenced global energy transition.[18] Countries that invest in these production pathways can also trade with those that have significant centers of demand. Already, these countries with demand centers are exploring opportunities to invest in supplying countries and own equity in projects, beyond just offtake agreements. For example, the Japanese company Eneos invested in a U.S. Gulf Coast hydrogen company.[19]

Hydrogen can also increase domestic and international energy security, reducing fossil energy imports and diversifying energy resources available to countries to meet growing demand. In the wake of Russia-Ukraine war and the resulting energy crisis, many nations—particularly in the European Union—were reminded of their dependence on foreign energy resources, 80% of which still comes from fossil fuels today.[20]

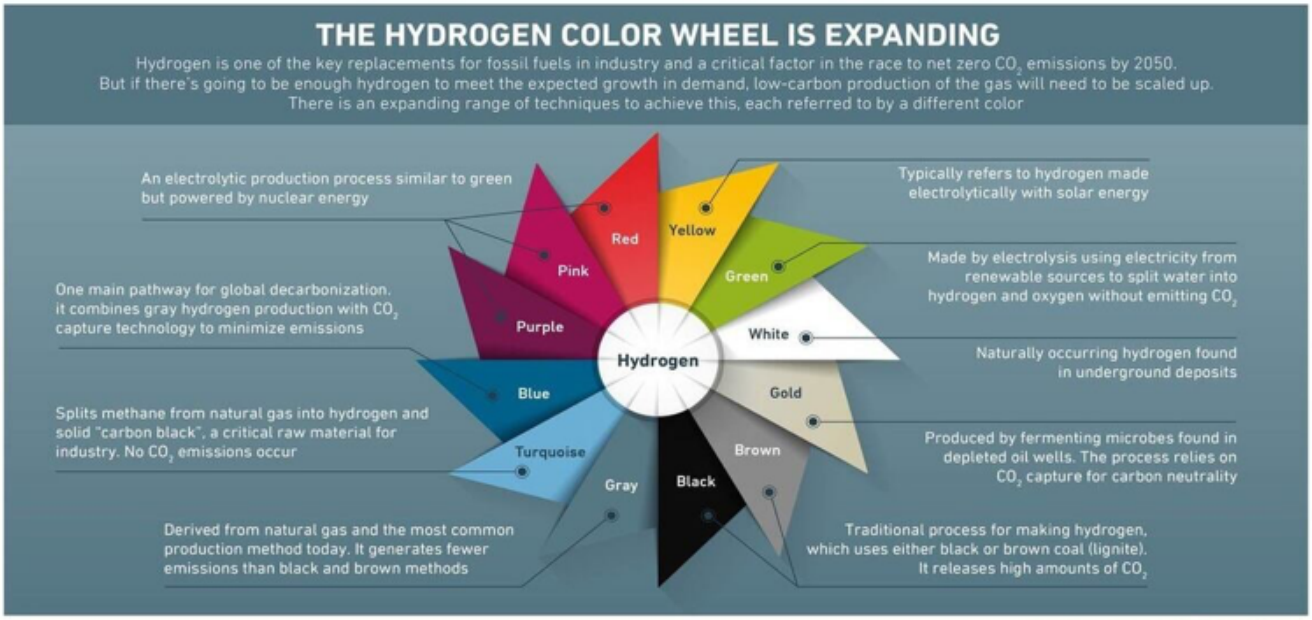
Framing the Global Hydrogen Industry Today

While hydrogen production and consumption exist today, its production is emissions-intensive. Steam methane reforming (SMR) without carbon capture, utilization, and storage (CCUS), i.e., gray hydrogen, represents 62% of global hydrogen production, followed by coal gasification—the dominant production pathway in China—at 21%. In comparison, clean hydrogen pathways (i.e., SMR with CCUS or electrolysis) represent less than 1% of global production.[21]

Green hydrogen is defined as hydrogen produced by electrolysis of water using renewable electricity. Blue hydrogen is defined as hydrogen produced from natural gas through SMR with carbon capture and storage (CCS), which traps CO_2 byproducts. Many experts have stated that blue hydrogen presents a window of opportunity during the transition to green hydrogen.[22] The hydrogen “rainbow” or “color wheel” in Figure 1[23] is a tool we use to describe different methods of producing hydrogen. It indicates the carbon intensity of each process.

Currently, hydrogen use is largely confined to the petrochemical and fertilizer industries. In 2022, 95 million metric tons (MMt) of hydrogen (H_2) were consumed globally, an increase of 3% from 2021.

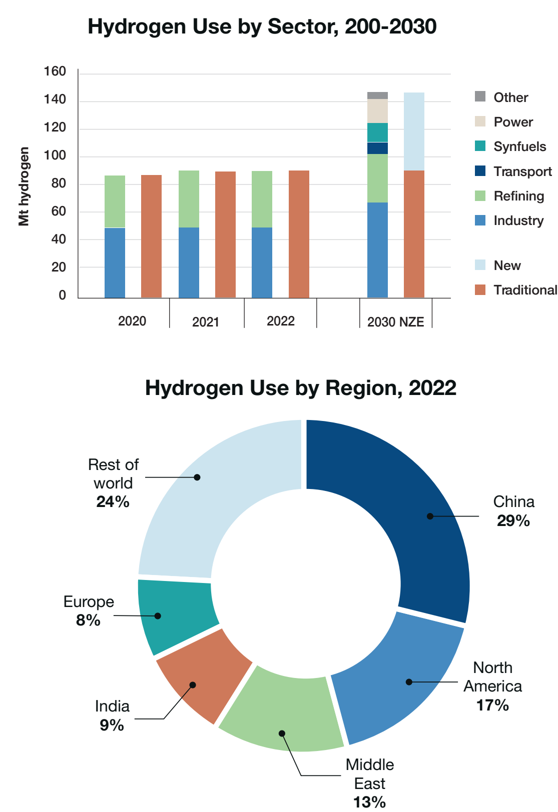
Figure 1. Hydrogen color wheel



Source: Mitsubishi Heavy Industries Group, The Color Wheel, 2024, https://spectra.mhi.com/the-colors-of-hydrogen-expanding-ways-of-decarbonization.

The United States alone produces approximately 10 MMt annually.[24] However, the industry's marginal increase came almost entirely from traditional applications in the refining and chemical sectors, using unabated fossil fuels for hydrogen production.[25] Regarding existing demand, the refining industry consumed more than 41 MMt H_2 in 2022.[26] Another 53 MMt went to the global industrial sector, where 60% was used in ammonia production, 30% for methanol production, and 10% for direct reduced iron steelmaking.[27] China is currently the world's largest producer of hydrogen, making nearly 30% of global supply, which is roughly equivalent to the total hydrogen consumption in North America and the Middle East combined (Figure 2). Importantly, China uses nearly all of this hydrogen in traditional chemical applications, mostly in domestic fertilizer production.[28] While these traditional end-uses present a key demand source for clean hydrogen, expansion into new demand applications—whether in heavy industry, transport, hydrogen-based fuel production, power generation, or storage—remains relatively nascent on the global scale, accounting for less than 0.1% of global demand.[29]

Figure 2. Current and projected hydrogen use by sector and region, 2020-2030



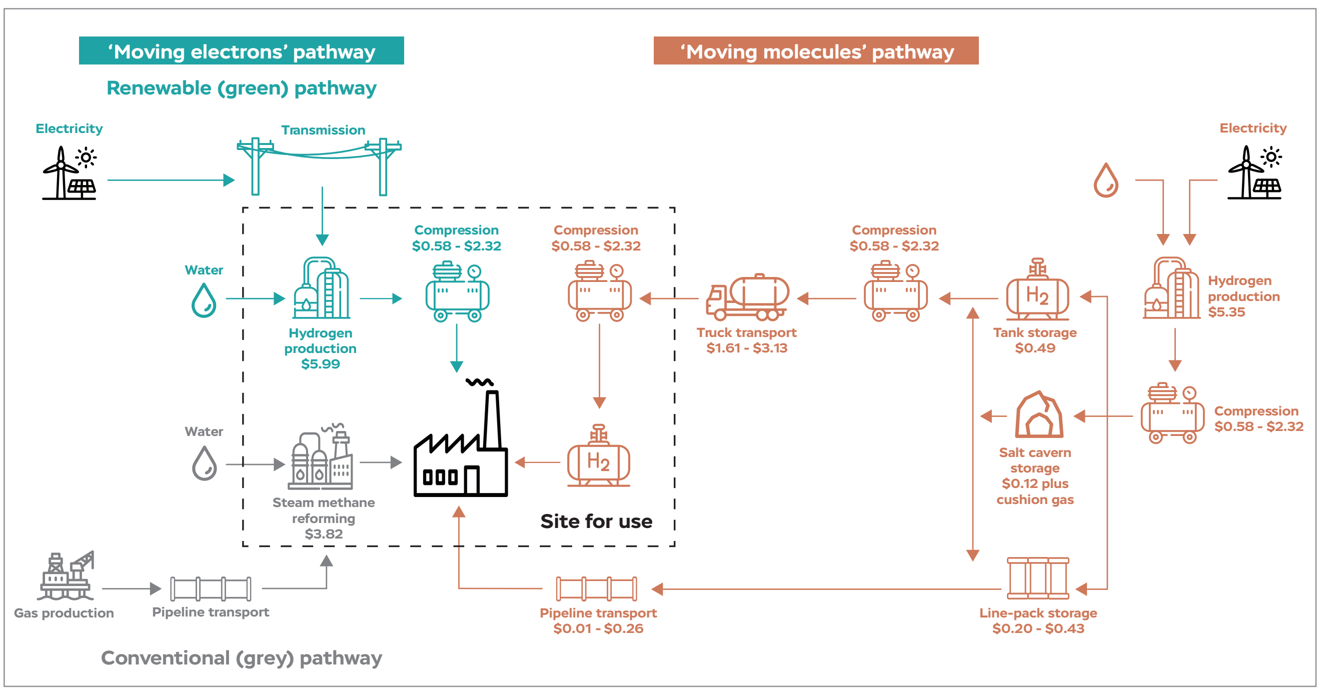
Source: IEA, Global Hydrogen Review 2023, September 2023, p. 21, https://www.iea.org/reports/global-hydrogen-review-2023.

Cost competitiveness presents a major challenge to scaling up the global clean hydrogen market, as compared to different fuel costs and regional price variance. Hydrogen today is not traded as a global commodity, meaning the majority of production is co-located with the demand source and prices depend on fluctuating volumes required by traditional use cases. Prices also can vary significantly because hydrogen moves mostly through isolated regional markets or bilateral agreements.

In April 2024, the European Commission, in line with the REPowerEU plan and Green Deal Industrial plans, began awarding approximately $781 million to support the production of clean hydrogen (i.e., green hydrogen) through the European Hydrogen Bank. Out of 132 bids, 119 were considered eligible and seven were selected, with bid prices ranging from 40 cents to $4.90 per kilogram of hydrogen produced to meet the goal of 10 MMt of domestic green hydrogen production per year by 2030. Many observers have been skeptical of the EU program, citing that the investment needed to produce 10 MMt may be closer to $250 billion to $300 billion.

Another important consideration impacting the overall cost competitiveness of clean hydrogen is its shipping and transport costs, especially as they are much more expensive compared with oil and more expensive than LNG (Figure 3).[30] For hydrogen to be a market-viable commodity, it must be able to be traded in a market context, and to do that, it needs to be transported and stored appropriately and cost-effectively. This has led to much discussion of long-haul hydrogen shipping in a "carrier" (such as ammonia), even though two conversions would be needed for using pure hydrogen at the destination.

Figure 3. How hydrogen is produced and transported with associated costs[f]



Source: Mitsubishi Heavy Industries Group, The Color Wheel, 2024, https://spectra.mhi.com/the-colors-of-hydrogen-expanding-ways-of-decarbonization.

f Costs are in Australian dollars. The December 2023 exchange rate: $1 AUD = $.66 USD.

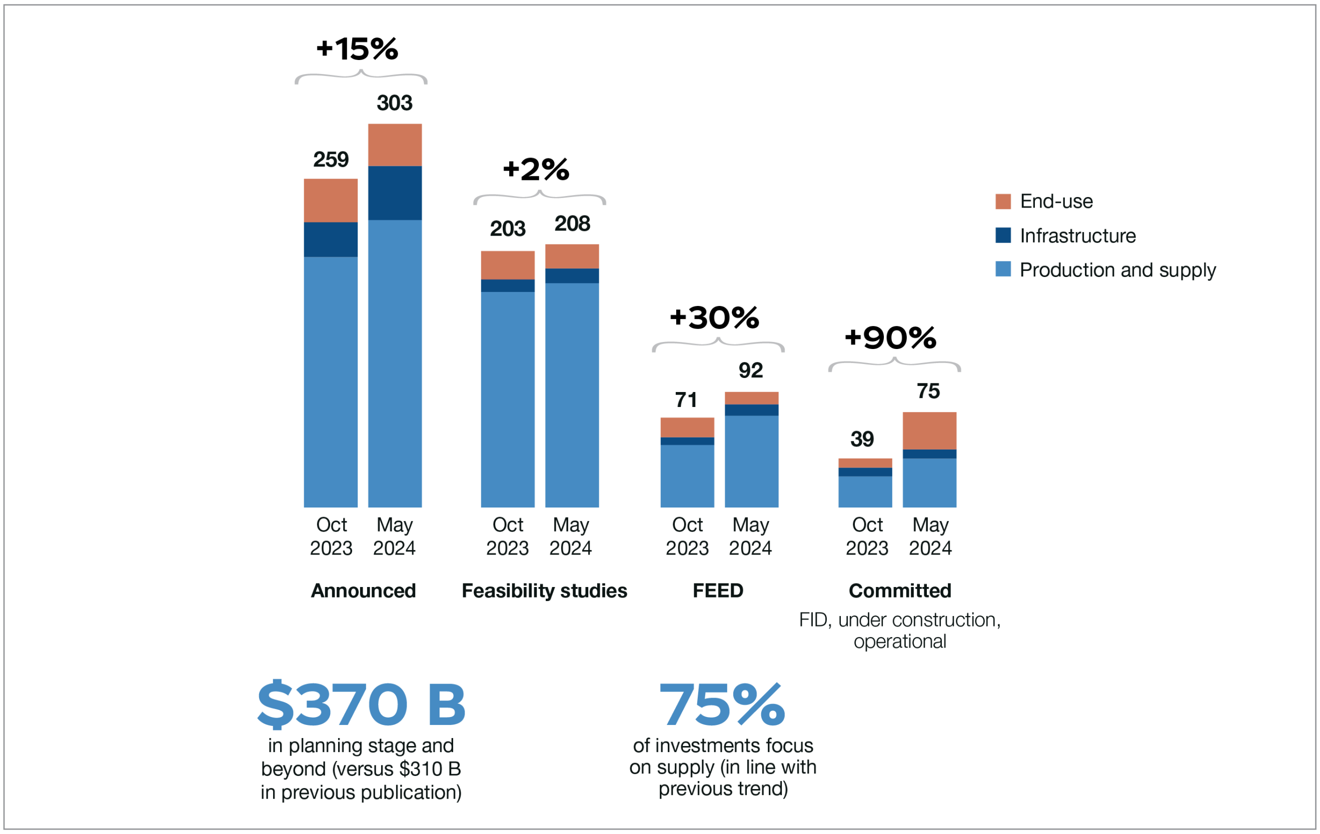
Despite the lack of a significant supply of clean hydrogen today, national governments and private companies globally have announced more than 1,572 projects and nearly $680 billion in direct investments through 2030 (Figure 4).[31] Approximately $75 billion has reached the final investment decision (FID) stage. Taken together, production from these announced projects would contribute 48 MMt H2/yr. by 2030, about 75% of which would come from renewable electrolysis and the remaining 25% from SMR with CCUS.

In terms of operational hydrogen projects, according to the Hydrogen Council, about 1.1 gigawatts (GW) of electrolyzer capacity had been deployed as of October 2023, or approximately 20% of what announcements indicated would be operational by that time.[32] These projects and investments are an essential component of organic bottom-up market development, especially for formulating regional solutions. The World Bank notes that hydrogen demand needs to increase fivefold by 2050 to meet the Paris Climate Accord's Nationally Determined Contributions (NDC) and net-zero goals. But for this to be achieved, the installed production capacity for green hydrogen will need to increase 75-fold between now and 2030.[33,34,g]

If that goal is achieved, hydrogen will still require demand from consumers and industry to be a viable energy source. While hydrogen has immense potential, it also faces numerous challenges, none more so than the price.

g NDCs represent efforts by each country to reduce national emissions and adapt to the effects of climate change. The registry of each country's NDC as of April 2024 is accessible here: https://unfccc.int/NDCREG.

Figure 4. Direct hydrogen investments until 2030, in billions of dollars



Source: Hydrogen Council and McKinsey & Company, Hydrogen Insights 2024, September 2024, p. 21, https://hydrogencouncil.com/wp-content/uploads/2024/09/Hydrogen-Insights-2024.pdf.

In addition to these bottom-up commitments and investments, top-down policy at a global scale is necessary to support the growth of clean hydrogen and encourage broader market development. Global market formation will, at an appropriate time so as not to stifle innovation, require international harmonization and cooperation on hydrogen regulation and certification to ensure countries can meet targets rapidly and pragmatically. This harmonization will, in turn, provide the foundation for greater alignment on hydrogen policy incentives, pricing, and distribution globally. So far, 41 countries have released hydrogen strategies that, together, could address 80% of energy-related CO_2 emissions globally.[35] **While these strategies have corresponded with hydrogen policy activity in these respective countries, they have largely ignored addressing new demand creation (MENA workshop).**

The issue lies in the fact that hydrogen, especially green hydrogen, is not currently produced in large amounts for use by new demand sources, such as transportation and power production, and is expensive to produce by low-carbon or no-carbon technologies. There also remains a massive gap in the infrastructure needed to transport hydrogen to new demand sources for significant uptake and use. These two issues are compounded by the fact that it will be difficult for a hydrogen market to develop without government intervention and support across myriad areas.

Some early new demand activity may be facilitated through bilateral and multilateral hydrogen trade agreements. Since August 2022, 27 countries have signed 31 bilateral agreements specifically related to hydrogen.[36] In 2023, nations producing and consuming hydrogen also saw greater multilateral cooperation, such as through the Clean Energy Ministerial Hydrogen Initiative.[37] At the same time, activity on the regulation and certification front has created greater confusion for investors and project developers. Already, seven national and international frameworks are in place for Guarantee of Origin certifications and six more national frameworks are forthcoming, all of which are a mix of voluntary or regulatory measures.[38] The variety of potential clean hydrogen production pathways will change the total embodied emissions of hydrogen and its infrastructure across its life cycle. For the hydrogen industry to move beyond bilateral agreements and into a global commodity market, these frameworks will require synchronization.

Workshop Findings

As noted in the letter from the presidents of EFI and KAPSARC, this study is structured around three cross-cutting workstreams and related workshops. The report from the first workshop, A Global Hydrogen Future Workshop, used each of these components to highlight 10 major takeaways, detailed in Figure 5. These have served as the foundation of this broader report.[39] As a record of this project launch, A Global Hydrogen Future – Workshop Report (with three white paper attachments) was released in March 2023.[40]

Figure 5.

Key Takeaways From A Global Hydrogen Future Workshop

1

Applicable regulation exists today to spur initial hydrogen development; however, more regulation is needed on the demand side to enable the true market potential of hydrogen as an energy commodity.

Participants noted the need for more regulation in several high-priority areas to fully realize the potential for hydrogen as a key energy commodity and carrier. Such areas included policy to support market development, which could mean standardizing the definition of “clean” hydrogen and derived commodities or implementing Carbon Border Adjustment Mechanisms (CBAM).

2

Advocacy and buy-in are necessary to the development of a hydrogen market.

Hydrogen as a fuel and feedstock is commonly misunderstood, and incorrect perceptions could impede development. Participants discussed how sharing early hydrogen success stories could enhance community awareness and facilitate the uptake of hydrogen as a fuel source.

3

Global data standardization applied on a regional basis is essential for hydrogen market development.

Throughout the conversation, there was consensus that greater standardization is needed for data sharing. Consistency and transparency in hydrogen markets could mitigate price fluctuations and produce concrete outcomes of the producer-consumer dialogue to instill greater confidence in the industry and spur growth through investment.

4

Traditional oil and gas producers are well-positioned to be hydrogen producers.

Nations with active sovereign wealth funds could direct funding toward hydrogen market development, which could be leveraged further to develop hydrogen markets.

In addition, fossil fuel-producing nations can further decarbonize existing industries with low-carbon hydrogen production, e.g., large ammonia, methanol, and refining sectors.

5

The financial industry will require high-yield investments that demonstrate value across the supply chain.

Participants agreed that long-term offtake agreements, demonstrating demand or public-private partnerships may be needed for financing to occur at a scale sufficient to support regional and global market development. Another possible solution discussed was sovereign guarantees and blended financing, which would ensure a government backstop.

There was a consensus that the current focus on project finance is insufficient to develop regional and global markets and that policies must also attract equity market investments.

Figure 5.

Key Takeaways From A Global Hydrogen Future Workshop

6

Pricing hydrogen as an energy commodity will be challenging in the early stages of market development.

There was a consensus that pricing mechanisms for hydrogen need to insulate producers and end users from volatility risk and ensure confidence in a developing market.

However, participants disagreed as to how hydrogen should be priced. Pricing formation is seen as scaling up from a boutique industry, i.e., viewing hydrogen as a specialty chemical to a global fuel, or as part of the process of adopting an entirely new fuel source.

7

Midstream transportation challenges must be resolved to facilitate development of a global hydrogen market.

Participants noted the many challenges associated with transporting hydrogen molecules by ship and pipeline, such as liquefaction energy usage and the potential for leakage, which could diminish the climate benefits of building a hydrogen economy.

In addition, challenges exist with maintaining hydrogen purity and building infrastructure, such as pipelines, shipping vessels, and ports, which could be solved by local-level hub and spoke networks and policies for national or regional market creation.

8

The concentration of critical minerals and manufacture of electrolyzers represents a challenge to the widespread emergence of a green hydrogen economy.

Participants viewed China's control of electrolyzer and solar PV manufacturing as a potential restrictive single point of failure. However, the energy transition cannot happen without broad and deep international collaboration.

Production of hydrogen electrolyzers and fuel cells could drive up demand for nickel, platinum, and other minerals, even though the market effects will depend on the shares of the different electrolyzer types.

9

Increasing demand from Europe and Asia will spur the growth of a global hydrogen market.

The conversation on hydrogen demand cited Europe and Asia as potential markets, driven in part by decarbonization goals and energy security needs. Participants identified the ongoing crisis in Ukraine, as a lead indicator, which will drive multiple solutions to meet energy security and climate goals, including further development of renewable energy sources and clean fuels.

10

Hydrogen as a commercial fuel and ammonia as an energy carrier could help create demand growth.

To encourage hydrogen market development, the discussion centered on increasing the use of hydrogen as a fuel and for ammonia production. These uses were discussed as the primary options with the potential to increase hydrogen demand. Participants noted that the production of ammonia from low-carbon hydrogen would take advantage of existing infrastructure and will help to decarbonize global shipping.

Source: EFI, 2023

The second workshop focused on clean hydrogen development in the Middle East and North Africa (MENA) region. Recognizing both the potential for MENA to support the global energy transition and the challenge of scaling up the nascent hydrogen industry, the workshop centered the discussion on supply trends, demand patterns, and regulatory frameworks needed for the region. Figure 6 highlights the key takeaways from the workshop's expert panel and roundtable discussions.

Figure 6. Key takeaways and recommendations from the MENA workshop

- Global hydrogen market formation will require the industry to reframe hydrogen as a renewable energy deployer and a tool to build upon existing energy systems.
- MENA has the unique opportunity to Òplay both sidesÓ of the potential global markets for hydrogen export.
- In a changing geopolitical landscape, industry players are watching policy implementation in Europe, Asia, and the United States to guide their investments in regional hydrogen markets.
- Developers view imporvements in electrolyzer technologies as a major cost driver.
- The global hydrogen market will require greater international coherence on national strategies and international regulations

- There is still much debate surrounding the need for policy intervention and which policies can best facilitate global hydrogen market development.
- While subsidies can create demand for hydrogen, many developers have indicated a preference for greater regulatory guidance at this stage in market development.
- Beyond subsidies, carbon pricing mechanisms could encourage a global hydrogen market, but it will ultimately come down to price reduction.
- Midstream companents (i.e., transport and storage) of the hydrogen value chain represent a strong use case for public sector support.
- Different regions across the globe could benefit from well-designed public-private partnerships (PPP) that utilize the resources of national governments without stifling market-based innovation.

Source: EFI, 2024

Chapter 2: Opportunities for Hydrogen Demand

Hydrogen has the potential to support decarbonized energy demand throughout the global economy. While the transition of traditional hydrogen use cases to clean hydrogen is an important near-term demand opportunity, hydrogen can support additional decarbonization across various economic sectors. This chapter will explore hydrogen's potential as an energy carrier and clean fuel to decarbonize industrial applications while also expanding into heavy-duty transportation, power, and long-duration energy storage. These applications represent the most viable opportunities for global additional hydrogen demand creation. At the same time, each of these potential demand pathways faces significant economic challenges that come mostly from the high production costs of hydrogen compared with fossil fuels. The expansion of hydrogen into new applications must also deal with technical barriers to make the use of clean hydrogen a viable and affordable alternative to supprt decarbonization on a global scale.

The Need for Hydrogen as an Energy Carrier for International Markets

Global hydrogen market formation will require the industry to reframe hydrogen as a carrier of energy and a tool to build upon existing energy systems (MENA workshop). During the MENA workshop, experts discussed the possibilities of industrial policies for hydrogen. When it comes to industrial applications, it is important to frame hydrogen as an energy carrier deploying renewable energy in the most difficult-to-electrify sectors of industry. This framing connects industrial policy with carbon policy.

While hydrogen has the versatility to be deployed across applications, it also can be deployed across the world and then traded to facilitate global decarbonization. This is important because outside of the United States there is often a mismatch between where it is most cost-competitive to produce hydrogen and where demand is expected to be highest. Production costs depend on local renewable resources, electrolyzer utilization for green hydrogen, and local costs of natural gas and CCUS for blue hydrogen. Commercial potential also relies on the availability of other feedstocks, such as CO_2, to create synthetic fuels or iron ore for use in steelmaking. Lastly, a country's overall investment attractiveness (e.g., market efficiency, workforce availability, and country-specific risk factors), as well as public acceptance of new infrastructure, can greatly impact the commercial potential for clean hydrogen.[41]

Given these conditions, models of global hydrogen markets generally expect three categories of trading countries to come to fruition: countries with high export potential, countries with both cheap supply and large demand, and countries with significant demand but limited cheap supply (Table 2).[42]

Table 2. Categories of globally traded hydrogen producers and consumers

	Key market conditions	Examples of countries/ regions
High hydrogen export potential	Regions with lowest cost natural gas; exceptional solar radiation; powerful wind resources; strong export geographic location	Middle East, North America, South America, Southern Africa (Namibia, South Africa), Australia
Cheap supply and large demand	Ability to supply own domestic needs with low-cost natural gas and renewable resources; option to participate in global trade	China, North America
Large demand without cheap supply	Constrained land availability for onshore wind, solar, and fixed-offshore wind	Europe, Japan, South Korea

Source: EFI, 2024

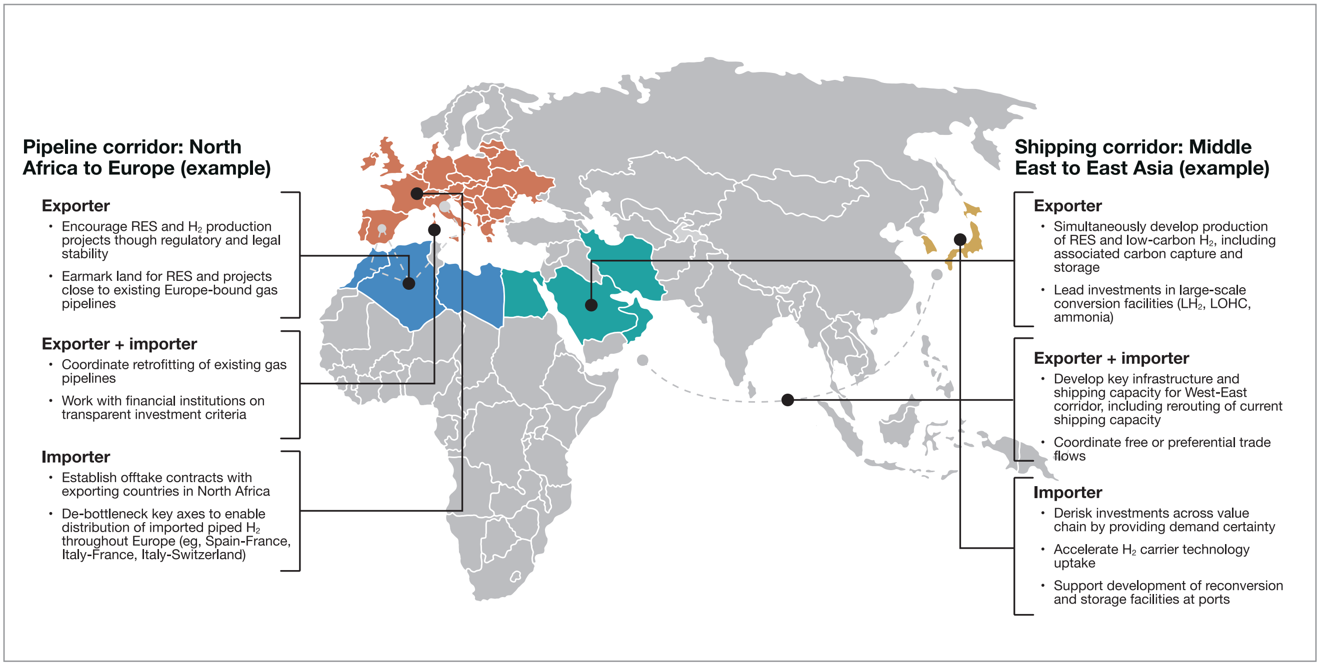
Increasing demand from Europe, Asia, and North America will spur the growth of a global hydrogen market (U.S. workshop).

Increasing demand from Europe, Asia, and North America will spur the growth of a global hydrogen market (U.S. workshop). Considering the major industrial sectors in Europe, Asia, and North America (as indicated by the above sections), these regions could support significant demand for clean hydrogen. However, Europe may not be able to meet this demand on its own, presenting opportunities for importing hydrogen. The conversation on hydrogen demand cited Europe and Asia as potential markets, driven in part by government-led decarbonization goals and energy security needs. Participants identified the crisis in Ukraine as a lead indicator that will drive multiple solutions to meet energy security and climate goals, including further development of renewable energy sources and clean fuels.

MENA has an opportunity to develop as a producer, consumer, and exporter in the potential global markets for hydrogen export (MENA workshop).

MENA has an opportunity to develop as a producer, consumer, and exporter in the potential global markets for hydrogen export (MENA workshop). The panel discussed how North Africa has easy access to the European market and the Middle East can connect with Japanese

Figure 7. Market conditions for global hydrogen trade: MENA example



Source: Hydrogen Council and McKinsey & Company, Global Hydrogen Flows: Hydrogen Trade as a Key Enabler for Efficient Decarbonization, October 5, 2022, https://hydrogencouncil.com/en/global-hydrogen-flows/.

and Korean markets, both of which are important geographic conditions for long-term hydrogen demand (Figure 7).[43] Importantly, actual offtake is virtually nonexistent, and these two regions differ regarding their perspectives on hydrogen regulation (i.e., where they expect to use hydrogen and their definitions of "clean" hydrogen based on carbon intensity). These conditions suggest a need for greater clarity and communication around regulatory requirements for off-takers to commit to long-term contracts, receive financing, and accurately forecast demand.

Hydrogen and derivative products can be transported through pipelines or on trucks, trains, and ships as liquified hydrogen. Transporting hydrogen in its gaseous form via pipelines occurs across the world today and is currently the most efficient form of transport up to distances of 2,500 to 3,000 kilometers (km) at a capacity of about 200 kilotons (kt) H_2/yr. To date, there are over 5,000 km of hydrogen pipelines operational globally, about 2,600 km of which are in the United States and 2,000 km in Europe connecting industrial users.[44,h] Planning for the expansion of this network is already underway in Europe through the European Hydrogen Backbone initiative (see Box 1 for more details).[45] Minimizing transportation costs by co-locating hydrogen production and use has been the choice up to now and is likely to remain so when it is possible.

h As of December 2023, an additional 600 km of hydrogen pipeline projects have reached FID.

Box 1. The European Hydrogen Backbone

The European Hydrogen Backbone (EHB) initiative combines the efforts of 33 energy and infrastructure companies to build a dedicated hydrogen pipeline network across the European continent, connecting supply with demand centers as well as integrated storage infrastructure.[46] One of the areas of expansion through the EHB is major hydrogen supply corridors in the North Sea and the Mediterranean. Additionally, there are plans to develop a Central European Hydrogen Corridor that would connect hydrogen supply from Ukraine to demand centers in Germany, given that Germany is expected to be the largest importer of hydrogen in the region. As of December 2023, the European Commission indicated its continued support of the Central European Hydrogen Corridor project and gave it "projects of common interest (PCI) and mutual interest (PMI)" status, despite the ongoing Russia-Ukraine war.[47] It is unclear, however, how the conflict will impact the implementation of this project.

The EHB intends to develop a 33,000 km pipeline network to connect hydrogen hubs and ports with supply. In addition to Central Europe, the plan will focus on hydrogen interconnections in Western, Central Eastern, and Southeastern Europe, as well as a Baltic Energy Market Interconnection Plan.[48] By 2040, the EHB plans to repurpose approximately 60% of Europe's natural gas grid across the continent. For reference, the EU has about 125,000 miles of fossil fuel-based pipelines that it will assess for hydrogen use in the future.[49]

Liquid hydrogen transport is another option for longer distances. Most of the advantages of this form of transport come from the liquefaction process—a commercially available technology—and the limited energy requirements for regasification and transport at import terminals. However, the volumetric energy density of liquid hydrogen is low compared to practical liquid fuels, and there are significant costs and energy losses associated with the equipment and shipping requirements, as well as scalability challenges.[50]

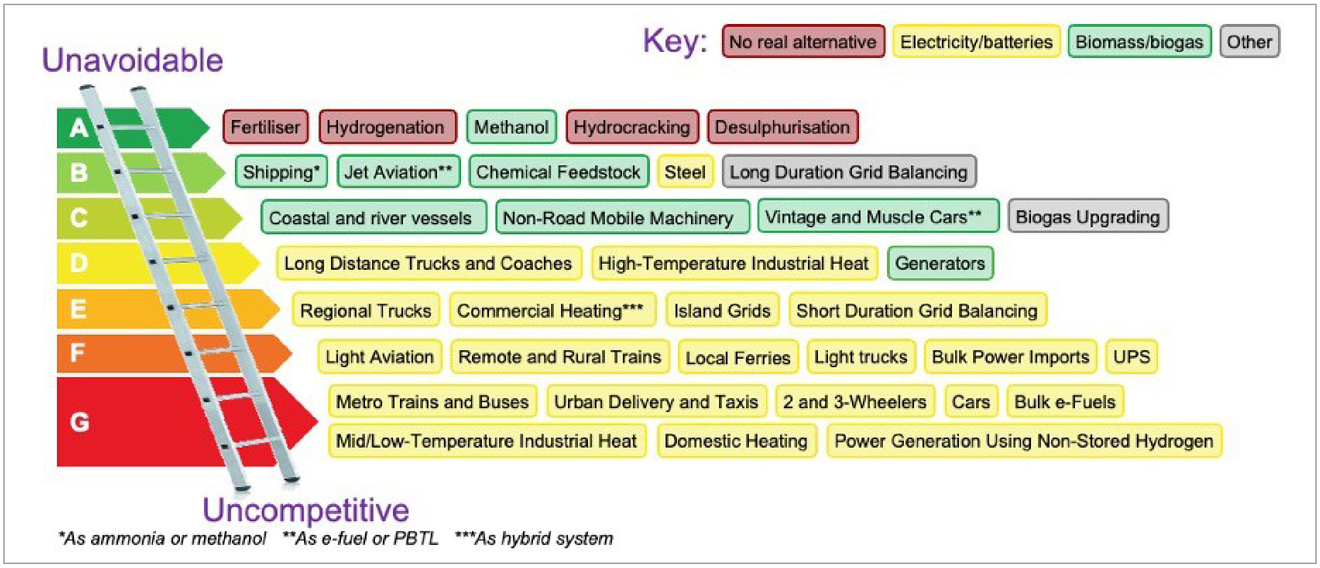
While there have been some new examples of the direct shipment of liquified hydrogen—particularly the Hydrogen Energy Supply Chain project connecting Australia and Japan—the associated technical and financial challenges make both ammonia and methanol stronger near-term options for long-distance energy carriers.[51] Recent reports have also relayed the uncertainty and complexities of hydrogen transport with liquid hydrogen, ammonia, methanol, and electrofuels[i] such as e-methane.[52]

i Electrofuels, or "e-fuels," are a class of synthetic fuels and a replacement "drop-in" fuel.

Potential Pathways for Hydrogen Adaptation

Many experts have debated where clean hydrogen will find inroads first, and each nation and region has the potential to develop differently. The following is a possible pathway—one that is described in greater detail in the white paper Hydrogen Market and Price Formation Considerations: A European Perspective among the supplemental material. The priority will be to produce green ammonia for the fertilizer industry and as a feedstock for the refinery and petrochemical industries, then to produce heat for those sectors and the steel, cement, aluminum, and paper industries. The second area will be seaborne shipping and aviation. The third will be land transportation. This will then be followed by use in power generation and heating. The clean hydrogen ladders for each segment are summarized in Figure 8[53] and in greater detail on Pages 56-59 of the white paper mentioned above. It should be noted, and emphasized, that such a scenario could look quite different in other parts of the world, such as North America.

Figure 8. Clean hydrogen ladder: Competing technologies



Source: Michael Liebreich/Liebreich Associates, Clean Hydrogen Ladder, Version 5.0, 2023, Concept credit: Adrian Hiel, Energy Cities, CC-BY 4.0, https://www.linkedin.com/pulse/hydrogen-ladder-version-50-michael-liebreich/.

Hydrogen as a Tool for Industrial Decarbonization

Transitioning existing uses of hydrogen to low- and zero-carbon pathways can reduce global emissions by about 1,300 MMt carbon dioxide equivalent (CO_2e) per year.[54] Fossil fuel-based hydrogen use today equals about 3.5% of global CO_2 emissions.[55] These emissions come predominantly from hydrogen's use in petrochemical refining, ammonia production, and methanol production. Given that these industries already use hydrogen in their regular operations, substituting clean hydrogen would function as a like-for-like fuel switch with few technical challenges[56] (assuming adequate space is available for a carbon capture facility in the blue hydrogen case).

The biggest case to be made for using hydrogen in industrial decarbonization is that it could replace natural gas as a fuel for high-heat needs. However, in these traditional hydrogen applications, it is important to recognize the investment and other business trade-offs between retrofits and new builds in these industries. In both cases, incentives or new regulations would be important to making a widespread transition feasible and timely.

Currently, natural gas is a key energy source and ingredient in industrial manufacturing. Natural gas is a key feedstock (here used as a chemical input to industrial processes),[57] provides affordable high heat needed for many industrial processes and supplies electricity for those industrial processes that can currently be affordably electrified. Depending on the production method, hydrogen could be a zero-emissions fuel that could fill the role natural gas plays. As noted, green hydrogen and blue hydrogen are produced using low-carbon methods. Further research and analysis are needed to best understand the economics of hydrogen fuel use for high-heat industries and future needs in light of full-electrification efforts. However, questions remain on the implications for natural gas supply and price.

Refining

Hydrogen is used in refineries to remove impurities, such as sulfur, and upgrade crude oil into lighter products (e.g., gasoline). Petrochemical refining represents the largest current end-use for hydrogen, accounting for more than 41 MMt H_2 demand in 2022.[58] Importantly, refineries service about two-thirds of this demand with hydrogen produced as a byproduct of refining processes. Currently, there is little incentive to transition this demand to clean hydrogen given that the use of byproduct hydrogen is the best option financially and infrastructurally as it is already deeply interconnected to refining and chemical businesses.[59]

However, any additional demand from these refineries could be met by the production of on-purpose hydrogen on-site using SMR or coal gasification.[j] At about one-third of refining hydrogen demand, on-purpose hydrogen accounts for approximately 10% of total refinery emissions. Clean hydrogen could directly replace on-purpose hydrogen demand, particularly with the addition of CCUS, once clean production pathways reach cost parity through technological advancements or policy incentives.[60] China is the largest current user of on-purpose hydrogen in refineries. More broadly, China has the world's second-largest refining capacity and consumes about 8-9 MMt H_2/yr.[61]

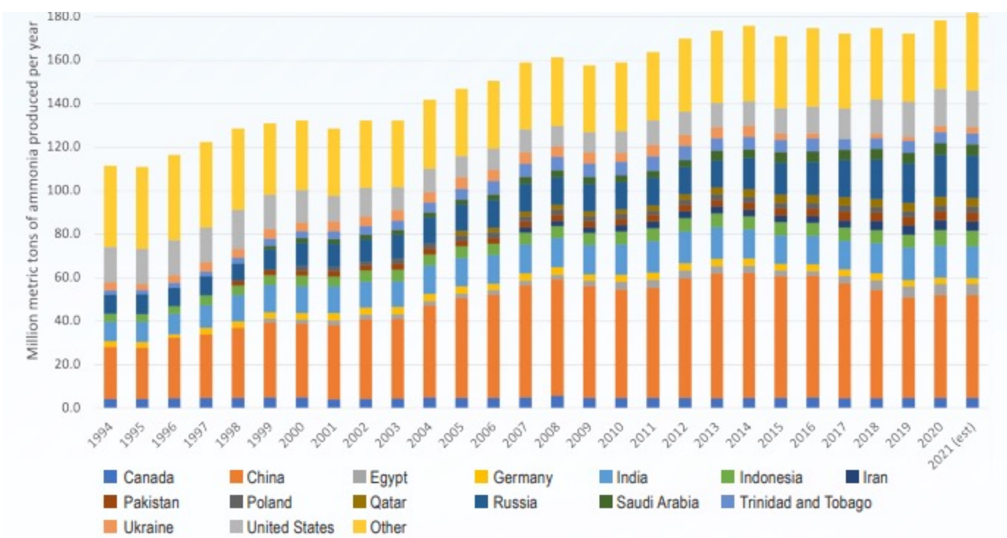
Ammonia

Ammonia production is the second-largest use case for hydrogen today; it used 33 MMt H_2 in 2021.[62] Ammonia is used primarily in global agricultural and food systems, where about 70% of ammonia is used as fertilizers. Industrial applications including plastics, explosives, and synthetic fibers use the remaining global ammonia supply.[63] The agricultural sector accounts for nearly 24% of global GHG emissions, and ammonia production alone makes up nearly 2% of global CO_2 emissions.[64,65,66] Of the 187 MMt of ammonia produced globally in 2021, the majority (72%) came from natural gas, followed by coal (26%), oil (1%), and electricity (<1%).[67]

The relatively low share of traded ammonia reflects the ammonia and fertilizer industry's focus on local production capacity to ensure national food security.[68] China is the largest producer of ammonia accounting for roughly 30% of global production, followed by Russia, the European Union, the United States, India, and the Middle East (i.e., Pakistan, Qatar, Saudi Arabia, and Iran) (Figure 9).[69] This distribution generally mirrors the demand for fertilizer; China and India have some of the largest agricultural sectors in the world.[70] About 10% of ammonia supply is traded as a global commodity among more than 100 ammonia-capable ports and nearly 200 ships equipped to handle bulk ammonia transport. (See sections that follow for more details on ammonia trade and its potential as a hydrogen carrier.)[71]

j On-purpose hydrogen production refers to on-site production via natural gas or coal that meets any shortfalls in hydrogen supplied as a refining byproduct.

Figure 9. Global annual ammonia production by country, 1994 to 2021



Source: David Sandalow et al., "Low-Carbon Ammonia Roadmap," Innovation for Cool Earth Forum, November 2022, p. 12, https://www.icef.go.jp/pdf/summary/roadmap/icef2022_roadmap_Low-Carbon_Ammonia.pdf.

The costs of ammonia production vary significantly by geographic location. While these prices have averaged around $305 per ton (t) since 2013, overall costs can range from $100/t to $1,000/t. Areas including the Middle East, Eastern Europe, and North America can produce the cheapest ammonia. China is the marginal producer and sets the global price. Regions like Western Europe, with significantly higher energy prices, face the highest production costs for ammonia.[72]

While it is technologically feasible to transition ammonia production to use clean hydrogen—either by adding CCUS to production from fossil fuels to create blue ammonia or by using renewable electrolysis for hydrogen production to create green ammonia—the costs remain high and have discouraged significant investment to date.[k] Ammonia is a price-sensitive commodity. Generally, ammonia plants have lifetimes of 50 years and high capital costs (approximately $1.675 billion for a typical plant), and a CCUS retrofit would require an additional 20% of that initial investment cost.[73]

k Decarbonized hydrogen used in ammonia production comes from biomass or water that is then combined with nitrogen purified from the air to produce ammonia using the Haber-Bosch process, where the hydrogen and nitrogen are combined at high temperature and pressure.

With the current costs of clean hydrogen today, blue ammonia production costs could range from $317/t to $824/t and green ammonia could range anywhere from $500/t to $2,000/t (Figure 10).[74]

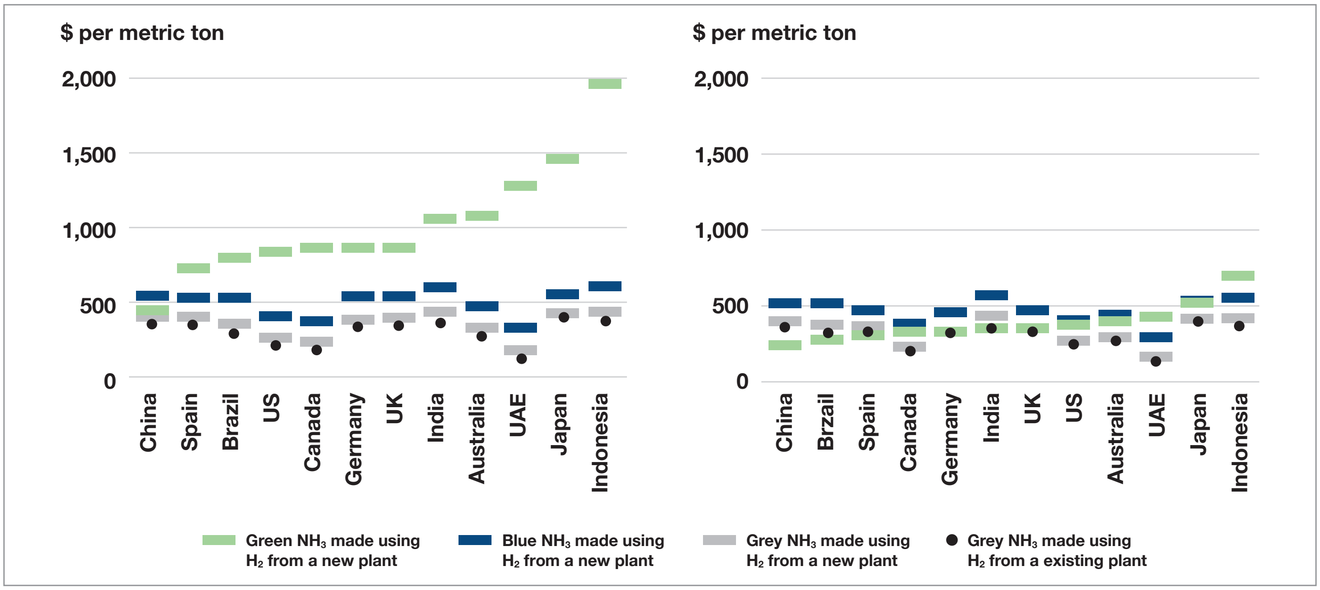
Ammonia as an Energy Carrier

Global trade of hydrogen today occurs on a small scale. As of 2022, the value of global hydrogen imports was only about $300 million. However, trade of hydrogen derivatives such as ammonia and methanol are well established, totaling $17.5 billion and $14.1 billion, respectively, in 2022.[75]

Framing hydrogen as a carrier of renewable energy to hard-to-abate sectors also applies to ammonia and methanol, which are among the derivatives often proposed as hydrogen carriers for long-distance transport given that these fuels have existing transport infrastructure in place across the globe.

This perspective is important when considering pathways for hydrogen demand in the future. The MENA workshop discussions also highlighted the potential for an even bigger reframing of the energy transition as an energy "expansion," emphasizing a phased approach that uses the existing economy and infrastructure where possible. This mindset becomes useful when considering the

Figure 10. Cost of ammonia production in 2023 (left) and 2030 (right)



Source: BloombergNEF and Climate Technology Coalition, Scaling Up Hydrogen: The Case for Low-Carbon Ammonia, January 11, 2024, p. 2, https://assets.bbhub.io/professional/sites/24/CTC-whitepaper_Ammonia_Final.pdf.

major challenge of transporting hydrogen. While some pipelines and ammonia ships exist today, countries have little incentive to build enough trucking, shipping, and pipeline infrastructure without corresponding demand. A MENA workshop participant suggested helping industry players better understand ways to build on existing infrastructure using hydrogen or other low-carbon energy sources to fill the gaps as demand grows.

Using hydrogen as a commercial fuel, and ammonia as an energy carrier, could contribute to the growth in demand needed to develop regional and global markets (U.S. workshop). To encourage hydrogen market development, the discussion centered on increasing the use of hydrogen as a fuel and for ammonia production. These were discussed as the primary uses that have the potential to increase hydrogen demand. Participants noted that the production of ammonia from low-carbon hydrogen would take advantage of existing infrastructure and help to decarbonize global shipping. In the transportation sector, ammonia could play a role as a flexible, non-emitting energy carrier for marine transport. If sufficient safety measures were put into place, ammonia could become a new drop-in bunker fuel for ships. Existing pipeline infrastructure, shipping routes, and ports that handle large quantities of ammonia are robust, which could enable a larger role for ammonia in the shipping industry. Ammonia production is, however, one of the largest industrial emitters of CO_2. A major reduction in emissions could be realized with a switch to clean hydrogen, as more than half of the emissions from the ammonia production process are associated with hydrogen production.

Ammonia has certain advantages over pure hydrogen when considering it as an energy carrier. Ammonia requires less cooling to be liquefied, has a higher volumetric energy density, and benefits from a well-established trade network of transport and storage infrastructure. Table 3 details the top importers of ammonia and each importer's top suppliers in 2021.[76]

Table 3. Top import markets for ammonia and top three suppliers, 2021

Importer	US$ million	Suppliers (percentage share in import market)
India	1,577.5	Saudi Arabia, Kingdom of (23), Qatar (22), Ukraine (13)
United States	1,352.2	Canada (48), Trinidad and Tobago (47), Algeria (1)
Morocco	769.6	Russian Federation (50), Trinidad and Tobago (36), Algeria (6)
Korea, Republic of	746.7	Indonesia (40), Saudi Arabia, Kingdom of (19), Trinidad and Tobago (12)
Belgium	521.0	Russian Federation (33), Trinidad and Tobago (24), Algeria (20)
Turkiye	453.1	Russian Federation (60), Libya (8), Algeria (8)
China	416.3	Indonesia (45), Saudi Arabia, Kingdom of (15), Malaysia (13)
Norway	368.6	Russian Federation (66), Trinidad and Tobago (10), United Kingdom (7)
Chinese Taipei	363.3	Indonesia (43), Saudi Arabia, Kingdom of (25), Iran (13)
Norway	340.5	Trinidad and Tobago (38), Algeria (14), Germany (13)

Source: IRENA and WTO, International Trade and Green Hydrogen: Supporting the Global Transition to a Low-Carbon Economy, December 2023, https://www.irena.org/Publications/2023/Dec/International-trade-and-green-hydrogen-Supporting-the-global-transition-to-a-low-carbon-economy.

While an existing import market for ammonia presents a foundation upon which to build a globalized network for trading clean hydrogen as an energy commodity, ammonia trade occurs only on a very small scale. As previously mentioned, despite China having one of the largest agricultural sectors globally, it is only seventh when it comes to ammonia imports because of its substantial domestic ammonia industry that ultimately stays within its borders.

Between 18 and 20 MMt of ammonia are transported by ship annually. Pipelines also transport ammonia within countries and between neighboring countries. The largest total distances of ammonia pipelines to date are located in the United States and between Russia and Ukraine, with shorter distances within Europe. European ammonia trade predominantly uses train transport. Some studies suggest that retrofits of both natural gas pipelines and liquid pipelines can facilitate the transport of ammonia as well.[77]

While there is potential to boost ammonia as a hydrogen carrier globally, the fuel has some technical and economic challenges that must be addressed. First, ammonia is a toxic gas at standard temperature and pressure and can pose rapid leakage risks if stored under high pressure in liquid form. As a result, ammonia is typically stored at standard pressure but cooled to its liquid form. For more than a century, ammonia handling and storage has occurred with few fatal incidents.[81]

Economically, a major barrier to ammonia's use as a hydrogen carrier is the need for catalytic cracking. This process refers to a decomposition reaction in which the ammonia is "cracked" to produce hydrogen and nitrogen gas. Even at 100% conversion efficiency, ammonia cracking consumes 13% of the stored energy of the ammonia. While there are commercially operational ammonia "crackers" in the metallurgy industry today, these systems function at very low capacities (1 to 1,500 kg H_2/day), operate at only 30% to 60%

Box 2. The NEOM Green Hydrogen Company project

The NEOM Green Hydrogen Company, a joint venture between ACWA Power, Air Products, and NEOM, completed the largest international offtake agreement for hydrogen, in May 2023, to produce green ammonia in a 30-year deal.[78] Ammonia production at scale is set to begin in 2026. The plant will produce 600 metric tons of carbon-free hydrogen per day—integrating 4 GW of wind and solar energy—that will support decarbonized transportation and industry globally and be used directly by Air Products. Specific applications for the green ammonia to be produced have not yet been publicly disclosed.[79] As identified in the EFI-KAPSARC MENA workshop discussion, the NEOM hydrogen agreement is the only successful global offtake agreement to date.

With the financial support of $6.1 billion in nonrecourse financing from 23 local, regional, and international banks and financial institutions, the NEOM project is valued at $8.4 billion and certified by S&P Global. Additionally, the already established engineering, procurement, and construction (EPC) agreements with Air Products are valued at $6.7 billion. The plant is being constructed at Oxagon in the Saudi Arabian region of NEOM. NEOM is a new urban area under construction by the Kingdom of Saudi Arabia that will house industrial complexes, global trading hubs, tourism, and residential centers powered by renewable energy.[80]

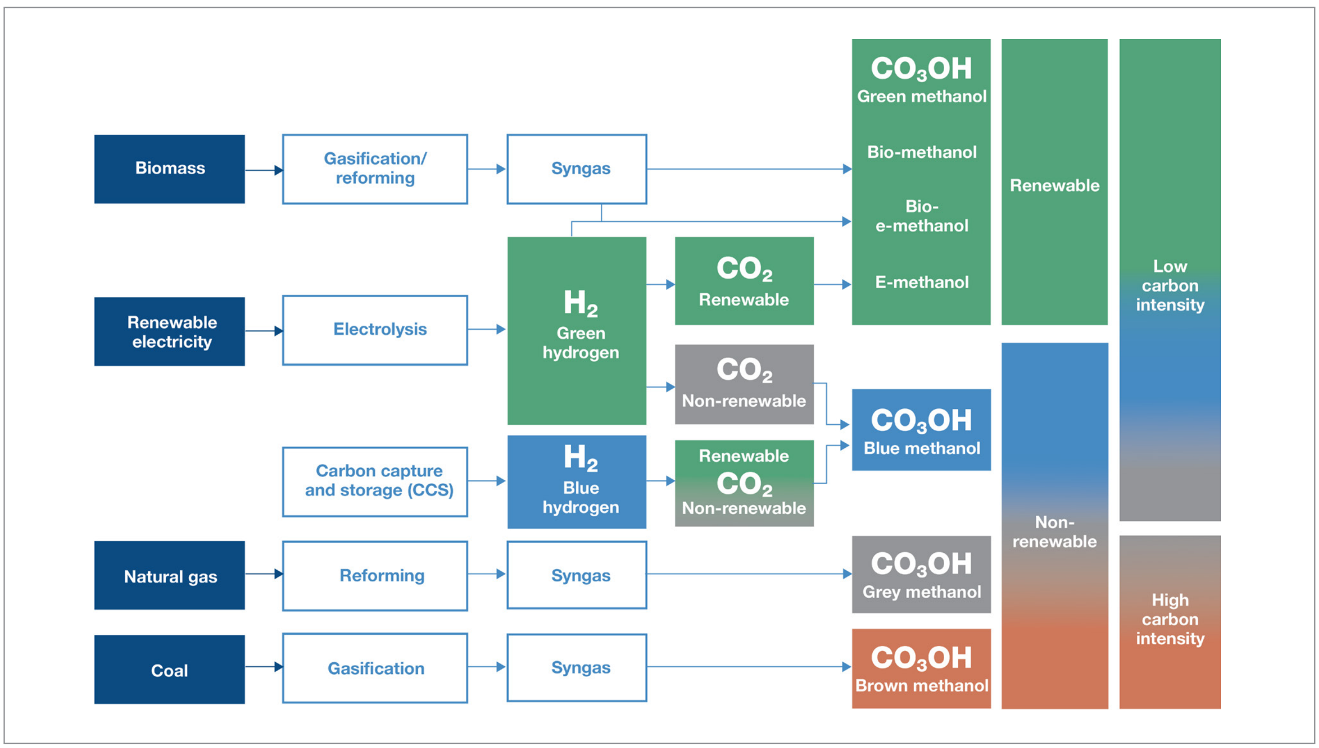
energy efficient, and require high temperatures (850 Celsius to 1,000 C).[82] For cracking to produce local hydrogen on an industrial scale, major improvements in energy efficiency and operating conditions would be necessary. In the case of green ammonia produced via renewable electrolysis, importing the fuel as a hydrogen carrier is cost-competitive only if the electricity costs in ammonia production are below $20/megawatt-hour (MWh), and the local renewable electricity used for cracking costs about $50/MWh.[83]

Methanol

Hydrogen also serves as a key ingredient in methanol production. Methanol is one of the four critical basic chemicals, alongside ethylene, propylene, and ammonia, used to produce all other chemical products.[84] The 2023 global supply of methanol was estimated at about 109 MMt. Demand for methanol has increased by 3.6% over the past five years, largely from its use in the chemical sector.[85]

Today, methanol production is almost entirely based on fossil fuels. Using either natural gas or coal, global methanol production emits approximately 0.3 gigatons (Gt) of CO_2 across its life cycle, accounting for nearly 10% of emissions in the chemical and petrochemical sectors. About 35% of global methanol production is synthesized with coal gasification, largely confined to China. The remaining 65% comes from natural gas reformation processes, with a small number of pilot projects using biomass and renewable-based feedstocks.[86] Hydrogen is already a main component of the synthesis gas (also known as syngas, principally a mixture of hydrogen and carbon monoxide) produced during methanol production. Figure 11[87] details the primary pathways to produce methanol, highlighting the opportunities for pathways with significantly lower carbon emissions intensity. Green e-methanol and blue methanol are the greatest near-term opportunities for hydrogen.

Figure 11. Current and potential pathways for methanol production



Source: IRENA and Methanol Institute, Innovation Outlook: Renewable Methanol, 2021, p. 23, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf.

Approximately 86% to 87% of global methanol supply and demand in 2020 came from Asia, with about 37% of supply and 40% of demand coming from China alone. This current demand is driven largely by the use of methanol in gasoline blends. China blends methanol into its gasoline mainly to extend the country's octane pool and make prices more affordable (generally the prices of crude oil and gasoline in China are relatively high). The next largest producer of methanol globally is the Middle East at about 8%. Europe and North America each account for about 5% of global methanol demand.[88] At the same time, China's methanol production almost exclusively comes from coal gasification. While Asia's market dominance and emissions intensity present a major challenge to decarbonization, they also represent a significant opportunity for near-term hydrogen demand. Compared to fossil fuel-based production pathways, green methanol can reduce CO_2 emissions by 60% to 95%, nitrogen oxide emissions by 60% to 80%, and almost all sulfur oxide and particulate matter emissions.[89]

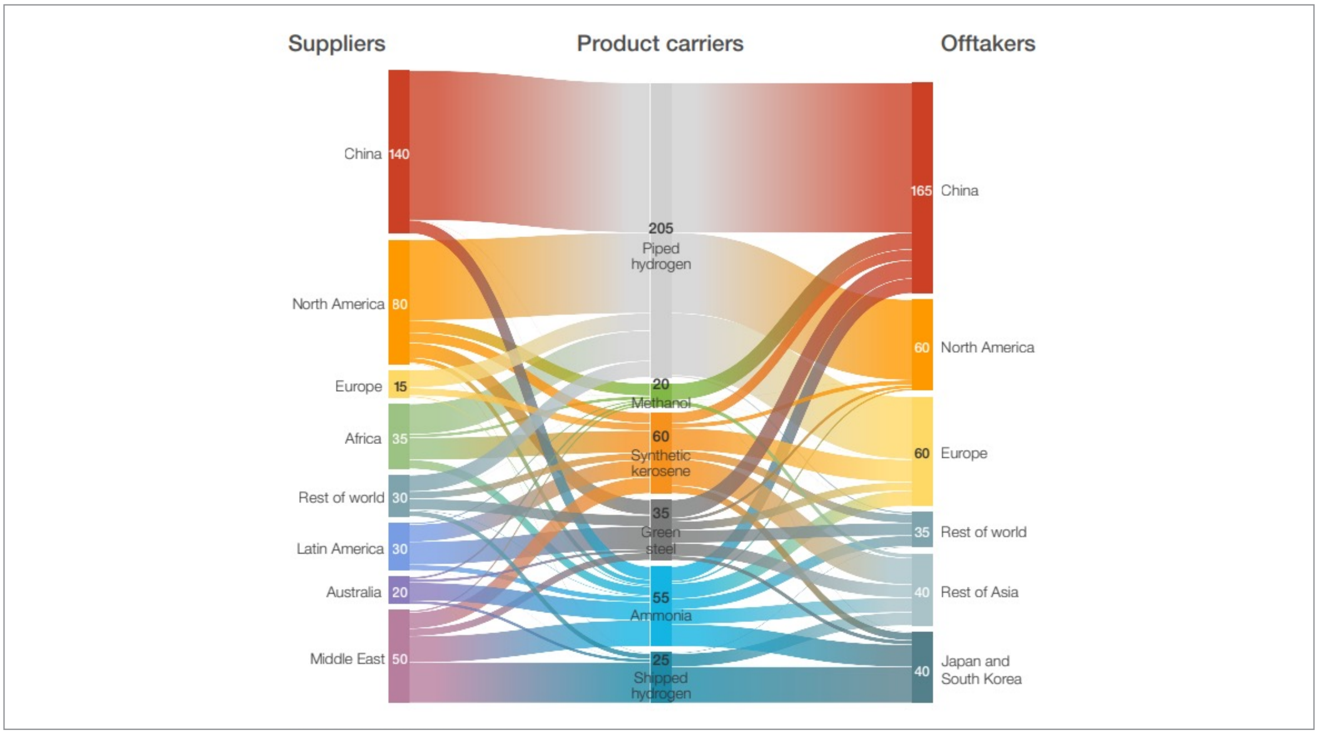
Methanol as an Energy Carrier

In addition to ammonia, some industries are looking to methanol as a potential energy carrier. Methanol—like ammonia—is traded as a global commodity, meaning the infrastructure already exists to store and transport methanol on a global scale. Methanol also presents an opportunity for carbon-neutral hydrogen transport if it is produced with sustainable feedstocks such as municipal solid waste, agricultural waste, and captured CO_2.

Some research suggests methanol has the potential to be cost-competitive with current fossil fuel transport markets in the 2030 time frame, particularly if hydrogen costs fall to 1.35 euros to 2 euros/kg H_2 ($1.47-$2.18) and CO_2 streams are available at 100 euros/t CO_2 ($108.78). In this scenario, the lower shipping costs associated with methanol balance out the costs of upgrading hydrogen to methanol.[90]

There are also challenges with using methanol as a hydrogen energy carrier. Logistically, methanol

Figure 12. Global hydrogen and derivate interregional long-distance supply, MMt/yr



Source: Hydrogen Council and McKinsey & Company, Global Hydrogen Flows: Hydrogen Trade as a Key Enabler for Efficient Decarbonization, October 5, 2022, p. 20, https://hydrogencouncil.com/en/global-hydrogen-flows/.

is highly flammable, explosive, and corrosive with some materials, similar to hydrogen. It is also highly toxic to humans. Economically, the most cost-effective solution to scale up the clean methanol market is to produce bio-methanol from biomass and waste products, a process that ranges in cost from $300/metric ton (t) to $1,000/t depending on the cost of feedstocks, capital expenditures, and operational expenditures.[91] E-methanol—methanol produced via hydrogenation of CO_2—is slightly more expensive at a range of $400/t to $1,000/t depending on costs for electricity production and for carbon capture. For comparison, methanol produced from natural gas ranges from $100/t to $300/t, and production from coal falls roughly between $150/t and $250/t.[92]

Taken together, the near-term development of international hydrogen and trade of energy carriers will likely implement a variety of technologies and derivative fuels to find the most cost-effective solutions for specific regions of the world.[93] Figure 12 explores the potential hydrogen transport pathways and derivatives to facilitate global demand looking out to 2050.[94] Across each of these options, it is evident that additional technological advancement and policy support is necessary to make these pathways economically competitive.

Steel

The global steel industry is another consumer of hydrogen today, though only in specific use cases. Globally, the most common form of steel production is the blast furnace/basic oxygen furnace (BF/BOF) process. This process, representing about 72% of global production,

Table 4. Crude steel production by process 2022

	Million metric tons	Oxygen (%)	Electric (%)	Other (%)
Asia	1,383.8	81.3	18.4	0.3
European Union	136.3	56.3	43.7	
North America	111.3	30.7	69.3	
Russia & other CIS + Ukraine	85.8	63.7	33	3.3
Middle East	50.4	5	95	
Other Europe	45.8	37.1	62.9	
South America	43.4	66.4	32.7	0.9
Africa	21.1	13.3	86.7	
Oceania	6.3	76	24	
TOTAL	**1,884.2**	**71.5**	**28.2**	**0.4**

Data from: World Steel Association, "World Steel in Figures 2023," May 2023, https://worldsteel.org/steel-topics/statistics/world-steel-in-figures-2023/.

requires the use of coal and is highly emissions intensive (2.2 t CO_2/t crude steel). The steel industry alone accounts for 7% of global GHG emissions and 11% of global CO_2 emissions.[95]
Asia is the largest producer of steel globally, producing 1,383 MMt in 2022 (Table 4). This is largely the result of major steel industries in China (1,018 MMt steel), India (125 MMt), and Japan (89 MMt). However, the industries in both China and Japan rely heavily on BF/BOF-produced steel at 91% and 73% of production, respectively.[96] To date, the majority of Europe's large steel industry uses BF/BOF production.

The other prominent form of steelmaking is known as the electric arc furnace (EAF) process, which is considered an "all-electric" approach and is significantly less emissions intensive (0.6 t to 1.4 t CO_2/t crude steel) than the BF/BOF process because it uses scrap steel as the primary feedstock. EAF can also incorporate direct reduced iron (DRI)—commonly produced with natural gas—that is then liquified and combined in the EAF to produce higher-grade steel at lower emissions than the BF/BOF process.[97,98,99] DRI-EAF is the dominant steel production pathway in regions of the world with an abundant and cheap natural gas supply, such as North America and the Middle East.[100] By region, the Middle East is the largest producer of DRI at about 38% of the 125 Mt DRI produced globally. Additionally, close to 95% of steel production in the Middle East follows the DRI-EAF process. About 70% of North American steel is made using DRI-EAF, and the region produces about 11% of the global DRI supply.[101]

Across Europe and Japan, national decarbonization plans emphasize the need for green steel production.[102] Hydrogen plays a role in the steel industry today mainly in combination with carbon, meaning there is currently little demand for pure hydrogen. Hydrogen could be a substitute for natural gas in the DRI process, either blended with natural gas or at 100% purity. This substitution, along with the use of zero-carbon electricity in the EAF, can create steel whose production is carbon-neutral. In the coming decades, as the steel industry transforms, a greater focus on DRI-EAF would not only increase hydrogen demand but improve the overall sustainability of the steel industry. One major carbon-neutral steel project already under construction is ThyssenKrupp's tkH2Steel, which can use either natural gas or hydrogen in steel production. The European Commission approved a 2 billion euro grant through Germany's national and regional governments to support this project, alongside ThyssenKrupp's 1 billion euro ($1.08 billion) initial investment. The company estimates this project will reduce annual emissions by 3.5 MMt CO_2.[103]

In the long term, there is potential to use hydrogen in the BF/BOF process, but this remains in the early stages of development. For example, in a trial, the Baowu Group—the world's largest steelmaker—is using hydrogen-rich and pure-hydrogen blast furnace and EAF technologies as a component of its road map to reach carbon neutrality by 2050.[104]
It is unlikely that BF/BOF steel plants will transition to DRI-EAF in the short to midterm, given the relatively young age of plants (average age is 13 years, which is a third of the typical lifetime[105]), the high capital costs, and the continued need for high-volume, low-margin steel products (e.g., primary steel). Countries producing this crude steel—such as China and India—face stranded assets as national pledges for carbon neutrality within the steel industry become more common. At the same time, these major steel-producing countries are in a strong position to lead global steel decarbonization and drastically reduce global GHG emissions.

Opportunities for New Hydrogen Demand

Outside of new demand opportunities within traditional hydrogen use cases, there are multiple pathways for clean hydrogen to support emissions reductions in nearly every sector of the global economy. Already, hydrogen investment announcements through 2030 have exceeded $570 billion. However, these announcements amount to just more than half of the estimated $1 trillion in investments needed by 2030 to meet net-zero emissions scenarios. Additionally, these investments skew toward the production and supply side of the hydrogen value chain, with the majority of this investment gap remaining among midstream infrastructure needs and end-use demand applications.[106] This section details some of the predominant areas in which infrastructure and end-use investments are expected and needed through the end of the decade to achieve net-zero emissions by midcentury.

Hydrogen in Shipping and Maritime Applications

Beyond hydrogen's role as an energy carrier in global trade, it can also directly fuel the shipping industry, either in its pure form or one of its derivatives (ammonia, methanol). As discussed at the MENA workshop, international shipping and hydrogen trade presents a huge opportunity for global decarbonization. Participants highlighted how international shipping is currently responsible for 1 Gt CO2/yr, or about 2% of total GHG emissions, a percentage that becomes important given net-zero targets and potential carbon border adjustments. The International Maritime Organization has committed to a 50% reduction in GHG emissions by 2050 and a reduction in sulfur-related emissions as well.[107]

Methanol could function as a maritime fuel, given its relatively clean combustion that does not release any sulfur, its low levels of particulate matter (PM) emissions, and its low nitrogen oxide emissions.[108] However, when combusted, methanol still releases CO2 emissions, which could be lower if sustainable sources of CO2 are procured, e.g., biogenic CO2. Currently, six methanol-ready ships are operating globally and more than 160 are expected to be in operation within the next few years.[109]

Ammonia also could be used as a fuel for the global shipping industry; it produces no carbon emissions when used as a maritime fuel. The Global Maritime Forum has identified 50 pilot and demonstration projects looking at ammonia combustion and hydrogen fuel cells, 30 projects on methanol, and 25 on hydrogen combustion in maritime applications.[110]

Still, these fuels face high upfront costs to be immediately used as shipping fuel. For example, even if renewable electrolysis-based hydrogen costs fell to around $2/kg H_2 by 2030, the resulting green ammonia would cost around $600/t to $700/t, which is roughly two to five times higher than the current price of heavy fuel oil used today. Additionally, the high capital costs associated with ship construction and the long lifetimes (approximately 30 years) of shipping fleets have also locked in much of the existing fossil fuel-based consumption across the global shipping industry. However, a growing number of new ship builds have incorporated designs for ammonia fueling retrofits down the road and implemented dual-fuel engines.[111]

Hydrogen in Aviation and Heavy-Duty Transportation

Hydrogen could also find application in heavy-duty transportation, particularly long-haul trucking, and aviation. The EFI-KAPSARC joint work program has completed collaborative research related to hydrogen's role in the global development of sustainable aviation fuels (SAFs).I SAFs are an alternative fuel pathway that can be directly substituted into current aircraft engine designs. They support near-term emissions reductions in the 2030 time frame as other technologies—such as hydrogen-based aviation fuel—reach technological feasibility.[112] SAF production requires clean hydrogen to account for about 15% of the jet fuel by weight. This process combines captured CO_2 with hydrogen to create high-density hydrocarbons that can enable fuel switching across the aviation sector.[113] This report finds that 65% of the decarbonization in the aviation sector can be

I Powering the Future of Aviation: Exploring the Role of Hydrogen and Power-to-Liquid in Sustainable Aviation Fuels, https://www.kapsarc.org/research/publications/powering-the-future-of-aviation-exploring-the-role-of-hydrogen-and-power-to-liquid-in-sustainable-aviation-fuels/.

achieved with SAFs, and its models suggest that hydrogen demand for SAF production could reach between 94.3 MMt H_2 and 224.5 MMt H_2 by 2050. However, achieving these quantities of hydrogen for SAFs will depend on a drastic increase in available renewable energy and sustainably sourced CO_2.[114]

Aside from aviation, the demand for hydrogen in other transportation sectors can also support decarbonization, especially heavy-duty vehicle mobility. By sector, mobility encompasses the highest value of committed investments in hydrogen end-uses, totaling $4.5 billion in 2023. There were approximately 79,000 fuel cell electric vehicles (FCEVs) on the road in 2023, an increase of about 20% from the previous year. Globally, there are more than 1,100 hydrogen refueling stations, largely concentrated in East Asia (China, South Korea, and Japan). Among vehicle manufacturers, most new FCEV models and general FCEV sales are gaining momentum in China's heavy-duty vehicle market, such as hydrogen-fueled buses and trucks.[115] This trend results from the increasing uptake of battery electric vehicles (BEVs) in light-duty applications and the continued challenge of electrifying long-haul transport. Still, one of the primary barriers continues to be adequate refueling infrastructure as hydrogen-based mobility transitions to heavy-duty and off-road applications (e.g., rail, air, inland shipping, port logistics).

Box 3. Case study: Australia-Japan hydrogen trade for heavy-duty transportation

Japan is expected to be one of the largest hydrogen consumers in the coming decades. Japan continues to be highly dependent on energy imports because of the country's limited domestic energy resources; it imports more than 95% of the energy and chemicals it consumes. As a result, Japan has begun developing international supply chains for hydrogen to repurpose its existing energy assets and secure energy imports in a decarbonized global energy system.[116] In particular, the Japanese government spent $141 million in FY 2020 on the development of hydrogen supply chains and imports.[117] Japan aims to reduce GHG emissions 46% from 2013 levels by 2030 and to reach carbon neutrality by 2050. Japan was also the first country to develop a hydrogen-focused road map—most recently revised in 2023—that targets use of 12 MMt H_2 by 2040.

The country intends to use hydrogen to decarbonize electric power generation (e.g., fuel cells, hydrogen-ready turbines), transportation (e.g., automobiles, shipping, aircraft, rail), and industry (e.g., steelmaking, chemicals, petroleum refining).

Japan is already a leader in fuel cell technology, especially FCEVs, as it is home to about one-quarter of the world's light-duty FCEVs and the world's second-largest hydrogen refueling network of more than 130 stations. Companies like Toyota are building commercial FCEVs.[118,119]

Beginning in 2012, Kansai International Airport (KIX), through a public-private consortium, aimed to transform itself into a "hydrogen airport" and is host to multiple pilot projects.[120] In 2015, KIX piloted the use of fuel cell forklifts to support airport logistics and passenger terminal transportation buses and even built a pilot track and a filling station with a test hydrogen fuel cell passenger vehicle.[121] In June 2022, Airbus and KIX partnered in a study on the use of hydrogen in aviation.[122] At Fukushima, Japan has also built one of the world's largest electrolysis plants with a capacity of 10 megawatts (MW).[123] More than 400,000 fuel cell power and heating units have been installed for residential energy needs across the country.[124] Additionally, other major sources of Japanese demand are the potential hydrogen hubs in Fukushima, Yamanashi, and Fukuoka prefectures being developed around major port areas. Private companies—including Mitsubishi, Toyota, and Air Liquide—have also initiated a joint venture to explore hydrogen hub development in the Chubu prefecture.[125,126]

Australia has become one of Japan's primary hydrogen trade partners. Australia is expected to become a global supplier of hydrogen, given its abundance of land and renewable energy resources to produce green hydrogen. In 2021, Japan and Australia agreed to the Japan-Australia Partnership on Decarbonization through Technology and, under the agreement, allocated 150 million Australian dollars for the Clean Hydrogen Trade Program to facilitate the production and export of hydrogen to Japan in January 2022.[127] Also in 2021, with federal funding support, the Japanese company Kawasaki Heavy Industries Ltd. constructed the world's first liquified hydrogen vessel and liquefied hydrogen receiving terminal, which received a shipment from Australia that year.[128]

Following this, in 2023, Japan pledged AU$2.1 billion ($1.42 billion) from its Green Innovation Fund to establish the world's inaugural liquefied hydrogen supply chain, in collaboration with Japan Suiso Energy, Kawasaki Heavy Industries, Iwatani Corporation, and the J-POWER and Sumitomo Corporation joint venture. This initiative, operating from Victoria's Port of Hastings in Australia to Japan's Port of Kawasaki, will extract hydrogen from Latrobe Valley coal with CO_2 capture and storage, to reduce emissions. The carbon intensity of the hydrogen will be verified through the Guarantee of Origin scheme and is aligned with goals set by the Intergovernmental Panel on Climate Change and the International Energy Agency.[129]

Internal analysis of this report's Global Hydrogen Database identifies at least four publicly announced trade agreements signed between Japanese and Australian companies, with an additional five agreements supplying Australian hydrogen to other East Asian and Pacific Island countries. Based on publicly available data, these agreements already surpass $80 million in private investment.

Hydrogen for Long-Duration Energy Storage and Load Following In-Power Applications

When it comes to power generation, hydrogen can act as a form of long-duration storage for renewable energy. Additionally, both hydrogen and ammonia have received interest as fuel substitutes in fossil fuel-based power plants to enhance grid load and resiliency and tto reduce power sector emissions. For ammonia in particular, there are opportunities to transition coal-fired power plants to use ammonia and contribute significant emissions reductions globally. To date, investments in hydrogen by the power sector globally amount to $1.2 billion.[130] Across North America, Europe, and the Asia-Pacific region, around 70% of projects using hydrogen and ammonia in the sector involve utilities exploring co-firing hydrogen with natural gas in combined-cycle turbines in the near term. In Asia, about 3% of these projects are testing the use of ammonia in coal-fired power plants. Another 10% of projects would implement large-scale fuel cells to produce power for regional electricity grids.[131]

Much of the activity in hydrogen-based power generation is concentrated in Asia (39% of announced projects), either co-firing hydrogen in natural gas-fired power plants or co-firing ammonia in coal power plants. Europe (36%) and North America (25%) make up the remaining share of hydrogen power projects. In total, these announced projects have the potential to increase the total installed capacity of power generation from hydrogen and ammonia to 5,800 MW by 2030.[132]

Another important use case of hydrogen in the power sector is long-duration energy storage for renewable electricity. This type of storage will be needed on the terawatt-hour (TWh) scale. Hydrogen stored in salt caverns presents the most cost-effective option for this type of storage compared with pressurized tank storage or liquified storage. Both the United Kingdom and the United States use underground salt cavern storage today for hydrogen and natural gas.[133]

An important consideration, however, is at what duration hydrogen storage becomes cost-competitive. From the perspective of roundtrip efficiency, the conversion from renewable power to hydrogen, then back to power is anywhere from 18% to 46% efficient, compared with more mature long-duration storage technologies like pumped hydropower, which has roundtrip efficiencies ranging from 70% to 85%.[134] However, hydrogen storage lasts much longer than that from pumped hydropower or grid-scale batteries, which operate on the time frame of hours to days. In contrast, hydrogen storage could enable seasonal load following for electricity grids and ensure longer-term energy security. Still, there are relatively few examples of significant investment in long-duration hydrogen storage to date, compared with grid-scale battery technology.

Hydrogen in High-Grade Industrial Heating and Processes

Beyond the new demand for hydrogen's use in its traditional applications (i.e., refining, ammonia production, methanol production), hydrogen can replace natural gas and coal in high-grade heating applications in the industrial sector. High-grade temperatures range from 200 C up to more than 1,000 C, and direct electrification, primarily from heat pumps or electric boilers, is currently not technologically feasible.[135] High temperatures are required to produce essential industrial goods, such as glass, cement, steel, and chemicals.

Hydrogen could facilitate decarbonization in the cement industry. Nearly 60% of all carbon emissions associated with the production of clinker come from the required process heating of at least 1,450 C.[136] To reduce the emissions from clinker production, transitioning this heat source from natural gas to hydrogen is possible. However, the costs of the product are particularly sensitive to fuel costs—representing about half of the final production costs—which could make the adoption of hydrogen as the primary fuel source too costly in the near term. Some research suggests that facilities may instead choose to simply add CCUS to their heat production, which would reduce emissions while avoiding additional fuel costs.[137] Already, Heidelberg Cement has conducted a pre-feasibility study at its Slite CCUS project in Sweden and is set for operation in 2024. This pilot intends to capture approximately 1.8 MMt CO_2/yr, which equates to 3% of Sweden's emissions.[138]

Similar to the steel industry, much of the cement industry develops products at a high volume and low margin, meaning that concrete prices are sensitive to added production costs. While there is potential for hydrogen's use in clinker production, significant progress in investment and commercialization is needed for hydrogen to have a role in cement decarbonization. Additionally, cement carbon neutrality will require pairing the use of hydrogen with CCUS across the full facility, further adding to production costs.

Hydrogen could also play a role in decarbonizing other emissions-intensive industries, such as glassmaking. While replacing the fossil fuels used in heating and power for glassmaking is possible, opportunities for full electrification, the use of clean fuels, or the addition of CCUS are not yet technologically or economically viable. To date, most furnaces used in glass production can accept only a 20% blend of hydrogen with natural gas given differences in thermal and radiative properties.[139]

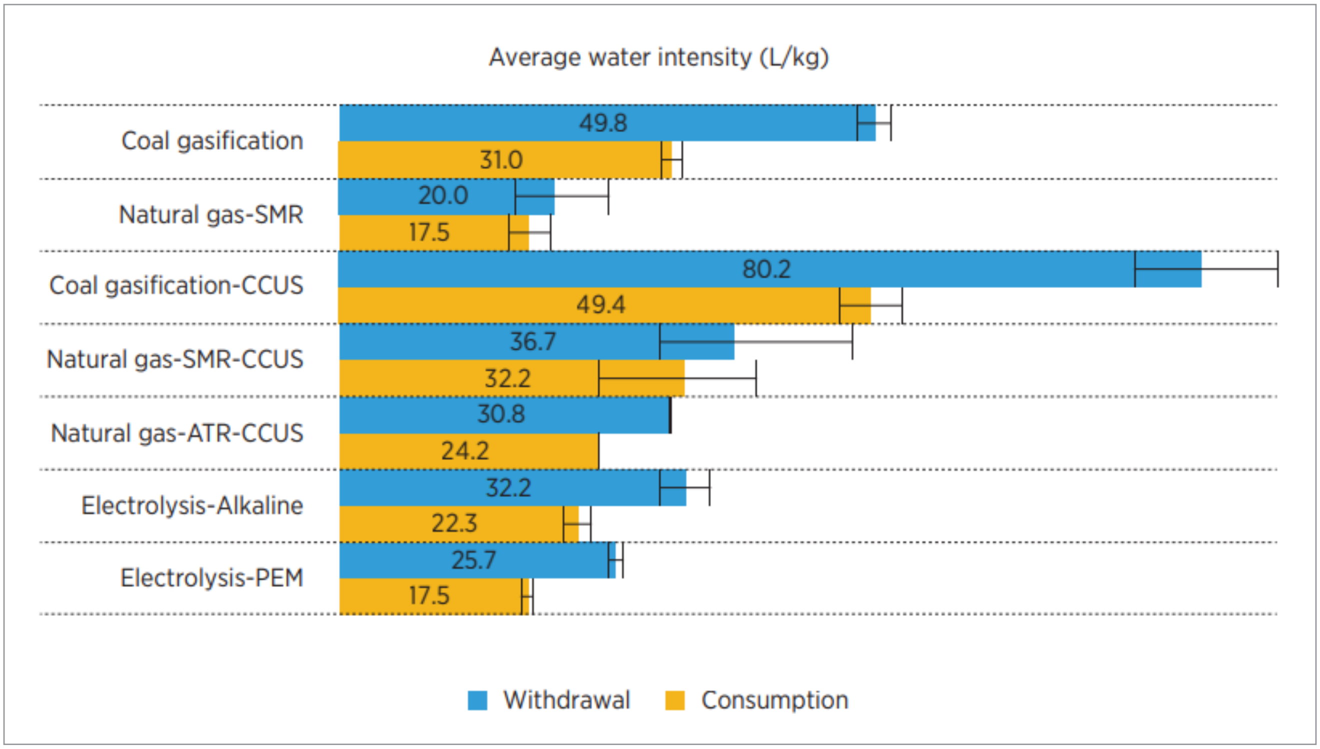
Hydrogen Blending in Existing Natural Gas Pipeline Infrastructure for Large-Volume Customers

Another potential area for increasing hydrogen demand in the short term is to blend it within the existing natural gas infrastructure. This demand creation was identified in previous EFI work, including the U.S. Hydrogen Demand Action Plan, where targeted blending for industrial customers and power generators—particularly those situated in clusters or hubs—could encourage emissions reductions on the order of 20 to 30 MMt CO_2e/yr. in the United States. However, this analysis also identified the significant scalability challenges that hydrogen blending faces because of technical limitations, mainly that hydrogen can embrittle steel pipes and its molecular mobility increases safety and operational risks compared with natural gas. The impacts on home heating and appliance operation and safety must be fully understood for highly variable settings.

While there is long-term potential for hydrogen blends up to 20%, it is expected that any hydrogen blending will be modest in natural gas pipelines until demand grows.[140] Some midstream pipeline transportation companies have stated during workshops that their "main focus will be on (1) given variations in pipes, when and of what material they were constructed, so that safety issues (embrittlement) can be addressed; and (2) there is a customer for the blend." Nevertheless, widespread hydrogen blending could make a material impact on near-term U.S. hydrogen market formation.

A similar situation exists in other parts of the world that are considering hydrogen blending into regional natural gas infrastructure. The European Commission has conducted technical assessments of the EU's pipeline infrastructure and found that any hydrogen injections into the natural gas grid should not exceed 5% to 10% to avoid major transmission modifications or end-consumer installations. With such changes, however, the European natural gas grid could potentially handle a 15% to 20% blend by volume. Still, using a 5% blending threshold could enable the addition of 18.4 GW of electrolyzer capacity and support the hydrogen strategies of a handful of EU member states (Spain, the Netherlands, France, Italy, Denmark, and Portugal).[141] However, for the EU in particular, neighboring member states will also need to harmonize their blending thresholds and safety standards to meet these goals, given the interconnectedness of Europe's natural gas grid.

Figure 13. A comparison of average water withdrawal and consumption intensities by production technology



Source: IRENA, Water for Hydrogen Production, December 10, 2023, p. 6, https://www.irena.org/Publications/2023/Dec/Water-for-hydrogen-production.

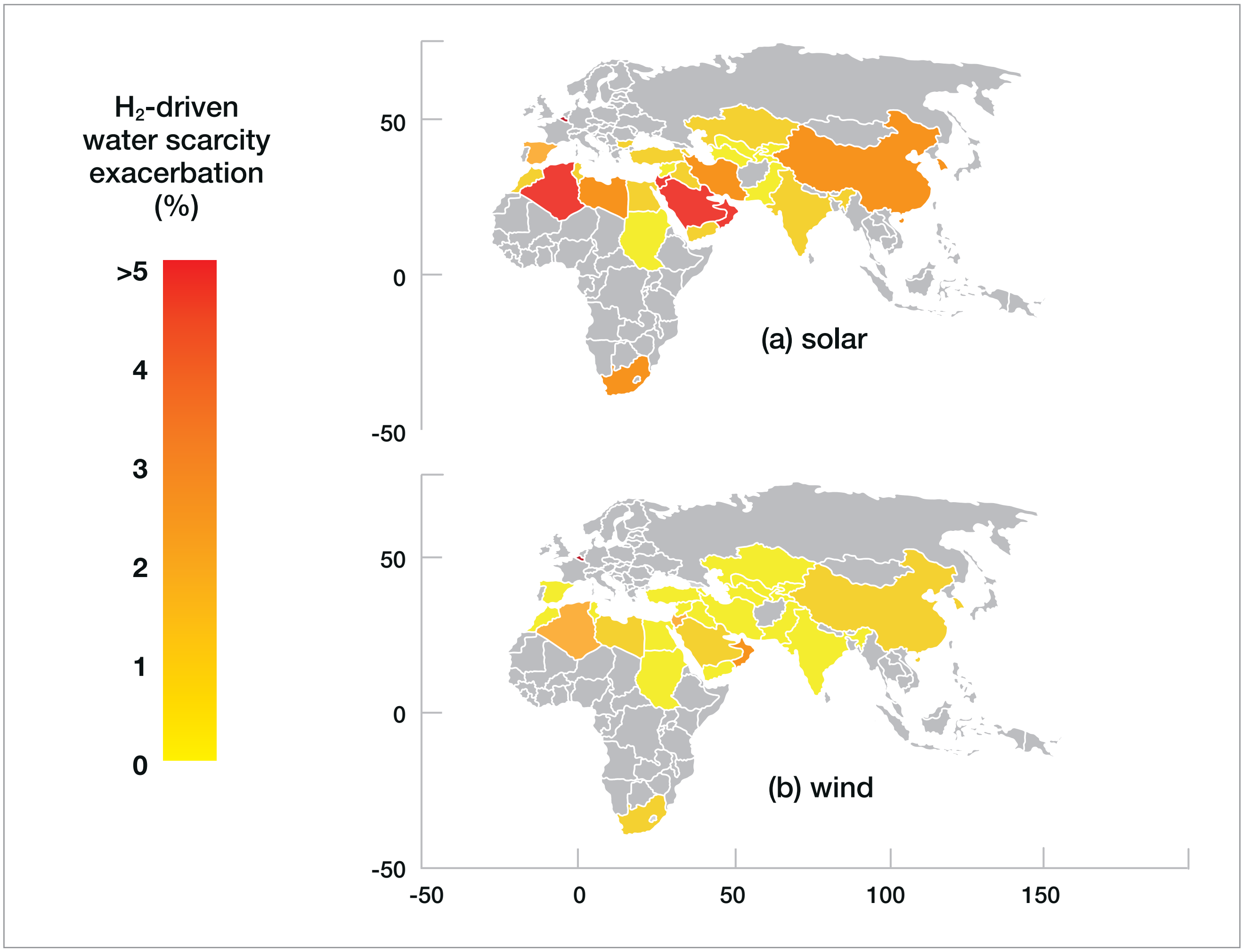
Possible Impacts on Water Availability from Global Hydrogen Demand Expansion

In addition to the various technical considerations already identified across the existing and potential value chain for clean hydrogen, another common concern with expanding clean hydrogen demand is its impact on global water supply. This concern is primarily related to the scaling up of electrolysis-based hydrogen production, which uses clean electricity to split water molecules and produce hydrogen gas.

However, analysis shows that compared with fossil fuel-based production pathways, electrolysis on average has a much lower water withdrawal and consumption intensity (Figure 13).[142] It is also worth noting that, for hydrogen produced via SMR with CCUS, the CCUS systems require significant water resources to cool the added heat transfer, in addition to the water needed for hydrogen produced via steam methane reformation. Additionally, for blue hydrogen production, there is substantial upstream water consumption from natural gas drilling, extraction, and processing.[143,144]

Despite its lower overall intensity compared with conventional fossil fuel-based pathways, water consumption in clean hydrogen production should account for the potential water displaced in regions of the world experiencing water scarcity. Recent research into this topic identifies the MENA region, Southern Europe, parts of sub-Saharan Africa, and much of Central and East Asia as particularly vulnerable to the potential magnitude of hydrogen production in those regions by midcentury (Figure 14).[145] These conditions point to the need for regional water availability assessments during

Figure 14. Modeled increases in water scarcity based on estimated hydrogen production in 2050



Source: David Tonelli et al., "Global Land and Water Limits to Electrolytic Hydrogen Production Using Wind and Solar Resources," Nature Communications 14, no. 1 (September 8, 2023): 5532, https://doi.org/10.1038/s41467-023-41107-x.

project planning, siting, water sourcing, and system design. Some potential solutions in water-scarce areas could include the consideration of alternative water sources, such as treated wastewater or desalinated water, the cost of which can be negligible, adding approximately $0.01 per kg of green hydrogen's cost.[146,147]

While there are important regional considerations regarding water scarcity and hydrogen production, the additional water use from electrolytic hydrogen production is relatively small compared with much larger water consumers such as agricultural irrigation and thermoelectric power on the global scale. One estimate suggests that assuming 660 MMt H_2 demand by 2050 worldwide, using entirely electrolytic hydrogen would require about 13.2 billion cubic meters of water, or about 0.33% of the global freshwater supply. Note that ultrapure[m] water is what is needed for electrolyzer applications. This analysis also does not account for the likely water savings that would result from hydrogen replacing fossil fuels in water-intensive industrial processes.[148]

m Ultrapure water or high-purity water is water that has been purified to uncommonly stringent specifications. The process to purify water may be one of the most expensive parts of production.

Chapter 3: National Policies and International Regulations

Recognizing the potential for hydrogen demand across sectors of the global economy, it is important to acknowledge that very little new, clean hydrogen demand exists today. The variety of potential applications for clean hydrogen use in the coming decades validates its importance as a decarbonization tool, but current investment risks and market uncertainties limit how far developers are willing to go with their clean hydrogen projects. While market forces can help determine which hydrogen production pathways and end-uses are most applicable to particular regions, policy intervention and regulatory clarity are essential to making these technologies cost-competitive and ensuring the international community can achieve carbon neutrality by 2050.

Currently, there are nine international initiatives—both governmental and nongovernmental—with overlapping objectives on research and development (R&D) collaboration, certification, policy development, stakeholder convenings, and deployment programs (Figure 15).[149] Similarly, the more than 50 national and regional hydrogen strategies predominantly focus on domestic hydrogen "hub and valley" planning as opposed to broader global collaboration.

This chapter will provide an overview of the existing global hydrogen policy landscape and national-level road maps, identifying gaps and inconsistencies. A walkthrough of potential global hydrogen price formation—using a historical comparison to the scale-up of the global natural gas market—will examine the factors contributing to the price of hydrogen and the dynamics in market formation.

Figure 15. International initiatives on hydrogen technology

Source: Fraunhofer, MENA workshop presentation 2023.

There is still much debate surrounding the need for policy intervention and which policies can best facilitate the development of a global hydrogen market. The rest of the chapter will focus on pathways to improve policy and regulatory cohesion globally. This includes a discussion on the development of international certification schemes for hydrogen and additional regulations needed to ensure the sustainability and traceability of hydrogen production and its use internationally. Additionally, this section will explore the policy solutions to rapidly incentivize the construction of a global hydrogen value chain. These insights draw from the key takeaways of the EFI-KAPSARC joint work program's two workshops on global hydrogen market development.

Existing Policies and Road Maps

Overview of National Hydrogen Strategies and Targets

As of December 2023, 41 governments, whose energy-related CO_2 emissions make up close to 80% of the global total, had adopted national clean hydrogen strategies. This effort is also scaling up rapidly, as almost 40% of these strategies were adopted in the last year alone.[150] In total, these ambitions amount to between 27 Mt H_2 and 35 MMt H_2 by 2030 and represent the largest driver of government funding for clean hydrogen.[151,152]

However, these targets overwhelmingly focus on the production side, meaning there are few examples of national-level targets and guidance for global demand creation. Policies that do exist today are largely confined to transport applications, such as subsidizing fuel cell electric vehicles (FCEVs) powered by hydrogen and the development of hydrogen refueling stations. A handful of demand-oriented policies in process could support market development beyond the transport sector, mainly because they are located in regions expected to have high hydrogen demand in the coming decades (e.g., Europe, the United States, China, Japan, and South Korea).

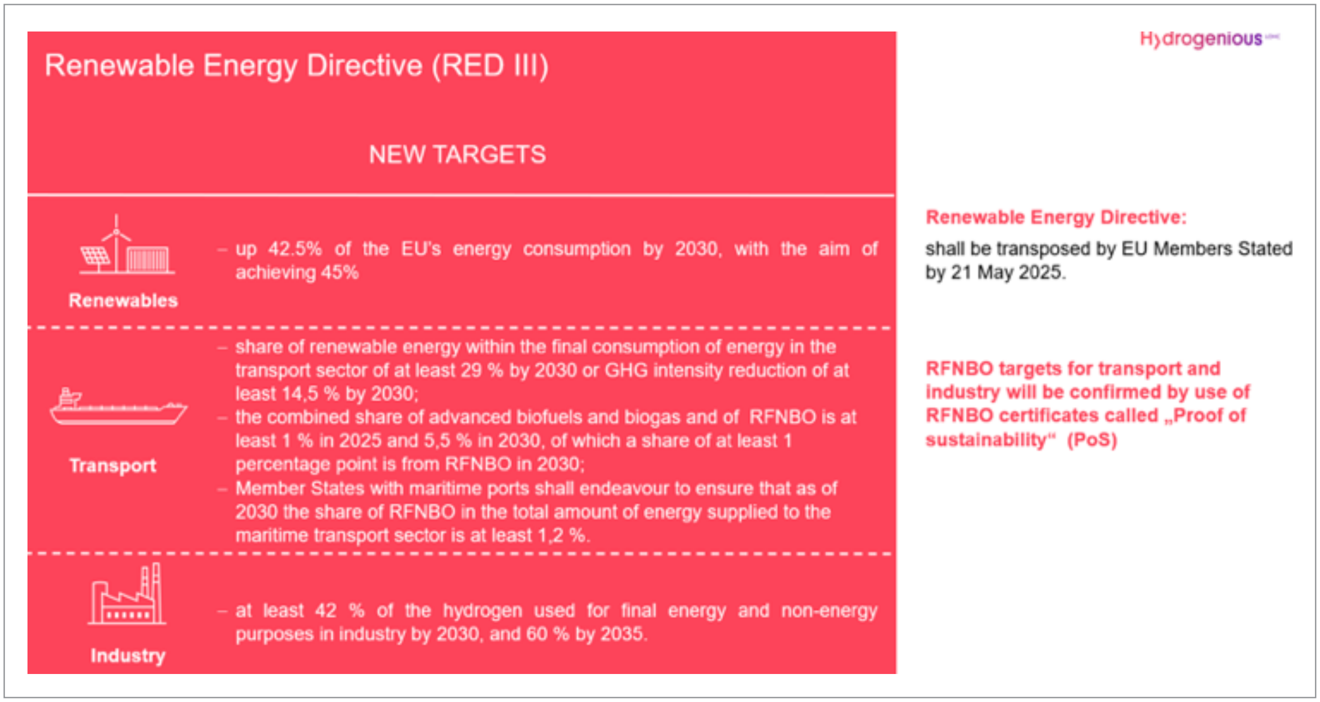
The United States' landmark Inflation Reduction Act of 2022 (IRA) includes a $3 tax credit per kilogram of hydrogen produced by renewables, which has created a powerful tailwind for hydrogen production. After the IRA, many nations followed suit with revised policies of their own such as REPowerEU in the European Union and Japan's Green Innovation Fund, which revised its Basic Hydrogen Strategy with new financial pledges of investment. All of these policies are aimed at increasing the size of domestic hydrogen markets.[153]

In Europe, one of the most influential pieces of legislation thus far is the hydrogen-related provisions in the "Fit for 55" policy package, referring to the EU's goal of reducing GHG emissions 55% by 2030. These policies fall under the EU's revised Renewable Energy Directive (RED III).[154] Importantly, these are binding and mandatory targets that were adopted in 2023 and require member states to use certain quantities of hydrogen in industry, transport, SAFs, and potentially maritime fuels in the short term (Box 4).

Box 4. The EU's Renewable Energy Directive's (RED III) hydrogen targets

In industry, 42% of hydrogen used must come from renewable fuels of non-biological origin (RFNBOs) by 2030 and 60% by 2035. In transport, at least 1% of renewable energy supplied to the transport sector must come from RFNBOs, including hydrogen, with a target of 5.5% by 2030.[155] Hydrogen was added to the ReFuelEU aviation initiative to decarbonize European aviation and other sectors (Figure 16).[156] For maritime fuels, the directive could introduce a target of 2% RFNBOs in maritime fuels by 2034.[157]

Figure 16. EU hydrogen targets through RED III



Source: European Parliament and Council of the European Union. "REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the Use of Renewable and Low-Carbon Fuels in Maritime Transport, and Amending Directive 2009/16/EC," 2023, https://data.consilium.europa.eu/doc/document/PE-26-2023-INIT/en/pdf.

Another important measure was provisionally agreed upon by the European Council and Parliament for a directive establishing rules for internal markets in renewable and natural gases. This directive aims to establish a regulatory framework for dedicated hydrogen infrastructure, markets, and network planning. Importantly, this directive also establishes rules for consumer protection and hydrogen supply security.[158] However, the actual regulation of this directive was still under debate as of March 2024.[159]

Unfortunately, while these regional targets are important mechanisms to increase public funding and have led some national governments to pass mandates, there is not yet adequate policy support on the demand side to realize these goals. For example, Romania passed legislation mandating hydrogen use in industry and transport—with penalties for noncompliance—to help the country meet the EU's decarbonization goals. However, given the lower-than-anticipated demand for clean hydrogen, Romania had to revise its strategy and cut its clean hydrogen production targets in half because demand was not sufficient in the transport and power sectors.[160] This is just one example where setting targets for hydrogen without complementary policies to spur demand can lead to incorrect assumptions and ultimately create a confusing investment environment for potential developers.

National, Regional, and International Incentive Structures

Multiple types of policy measures are already in force or recently announced to mitigate investment risks in hydrogen projects. About 35 of these policies across the globe use grants, competitive bidding schemes for hydrogen production, tax incentives, contracts for differences (CfD), and other mechanisms to encourage greater mid- to long-term stability for the hydrogen value chain to develop (Table 5).[161]

Table 5. Examples of recent policy measures to increase investment in hydrogen projects

Country	Policy	Status	Value Chain Segment	Description
Morocco	Grants	Announced	Production	In 2023, Morocco's state-owned chemical company OCP announced an investment of $7 billion in an ammonia plant that uses renewable-based hydrogen.
Denmark	Competitive bidding schemes	In force	Production	In 2023, the Commission approved a EUR 170 million (~USD 179 million) Danish scheme to support renewable hydrogen production.
Canada	Tax Incentives	Announced	Production	In late 2022, the government announced the Clean Hydrogen Investment Tax Credit to support 15-40% of eligible costs of projects for hydrogen production, with higher support for those with emission intensity under 0.75 kg CO_2/kg H_2. The 15% tax credit was extended to low-carbon ammonia production. The government also announced a CCUS Investment Tax Credit to provide a 50% credit for equipment associated with point-source CCUS projects, declining in 2030 and 2040 to incentivize early adoption. The proposal was in public consultation until June 2023 and the details of the design of the investment tax credit are expected soon.
Japan	Contracts for Difference (CfD)	Announced	Production	Japan will introduce a CfD on the difference between the price of renewable and fossil fuel-based hydrogen without the carbon price bench. The CfD will apply to companies supplying low-carbon hydrogen or ammonia.
Oman	Other mechanisms	In force	Production & Infrastructure	The government of Oman established Hydrogen Oman (HYDROM) in 2022 to structure large-scale "green" hydrogen projects, manage the auction of government-owned land for use by hydrogen projects, develop shared infrastructure, and support project development. The program functions as a fully owned, autonomous subsidiary of Energy Development Oman. In April 2023, HYDROM completed its first land allocation, and six hydrogen projects were awarded approximately $20 billion.

Data adapted from: IEA, Global Hydrogen Review 2023, September 2023, p. 152, https://www.iea.org/reports/global-hydrogen-review-2023.

In a changing geopolitical landscape, some industry players are watching policy implementation in Europe, Asia, and the United States to guide their investments in regional hydrogen markets (a statement from the MENA workshop). While European countries have many goals to use hydrogen, the war in Ukraine has created an energy challenge and a subsequent shift in policy to use foreign liquified natural gas (LNG) that could impact hydrogen development overall. At the same time, the Asian market prioritizes affordability, and hydrogen must become cost-competitive to penetrate the market, especially among developing nations.

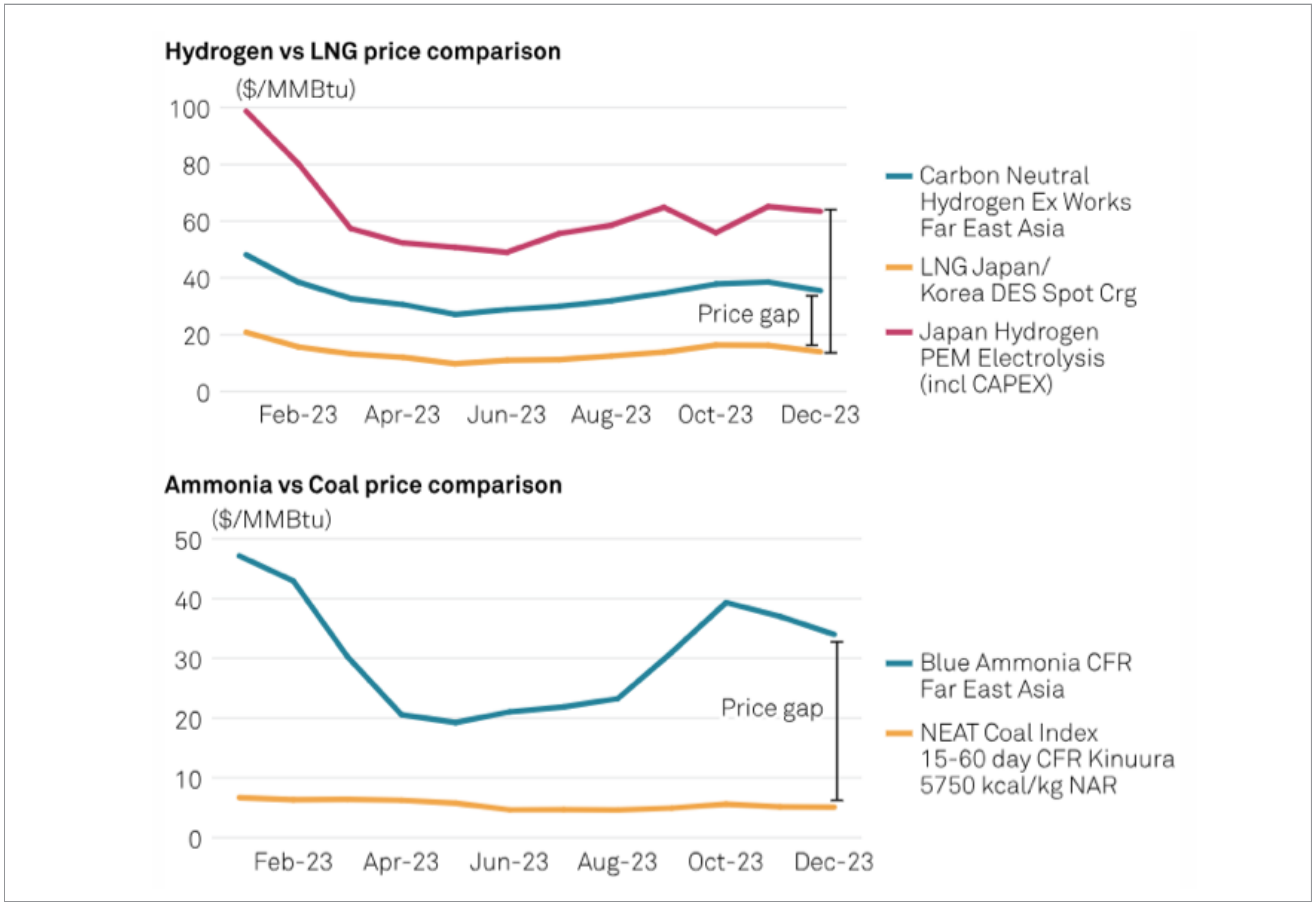
In a changing geopolitical landscape, some industry players are watching policy implementation in Europe, Asia, and the United States to guide their investments in regional hydrogen markets (a statement from the MENA workshop).

Regarding these global markets, stakeholders have varying perspectives on how demand will form. From the developer perspective, recent policies in the United States and Europe have enabled more investment, up to $1 billion dedicated to demand creation in the U.S. Department of Energy's (DOE) H2Hubs program and the H2 Global program in Europe.

Studies comparing these policies with Japan's plans for subsidies were announced in the second quarter of 2024. Some companies have already prepared feasibility studies to qualify for CfD in the Japanese market.[162] Once that process begins, projects could start reaching final investment decision (FID) more rapidly, making Japan a major player in the growth of the hydrogen industry.

Alongside Japan, South Korea is also developing policies to promote a regional market in Asia, particularly through CfD schemes, that will help ensure project bankability for the long term. Combined, Japan and South Korea have announced approximately 1.7 MMt in clean hydrogen capacity, but only about 1% of that capacity has reached FID, largely because developers are awaiting greater regulatory clarity and public funding announcements. The CfD schemes intend to bring more of this capacity to market by reducing the cost gap between unabated fossil fuel-based hydrogen and clean hydrogen production. Figure 17 visualizes this gap in cost in the Japanese and Korean markets, comparing hydrogen with LNG and ammonia with coal.[163]

Figure 17. Price gap between hydrogen and existing fuels in Japanese and South Korean markets



Source: Vipul Garg and Donavan Lim, "Clear Guidelines, Formation of CfD Schemes Likely to Unlock Asian Hydrogen Market in 2024," December 29, 2023, https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/122923-clear-guidelines-formation-of-cfd-schemes-likely-to-unlock-asian-hydrogen-market-in-2024.

For Japan, its CfD scheme includes a carbon intensity threshold definition of 3.4 kg CO_2e/kg H_2 well-to-gate target for 2030 to match international standards. The CfD scheme focuses on ammonia co-firing in existing coal power plants. This system would pay the difference between the strike price (i.e., the agreed upon price for the supply costs of hydrogen and ammonia) and the reference price (i.e., the price of counterfactuals like coal and LNG). In April 2024, Japan committed to spending approximately $19 billion on CfD subsidies for 15 years to reduce the cost gap between clean hydrogen production and fossil fuels.[164]

South Korea has defined 4 kg CO_2e/kg H_2 as its well-to-gate threshold. Under the bidding system for the CfD scheme, the system would use the levelized cost of electricity as the basis for bids and be made up of the system marginal price as well as the CfD. Market participants anticipate that the full CfD scheme in South Korea will be issued sometime in 2024. The country will begin the auctions under its Clean Hydrogen Power Standard, which is a CfD scheme to subsidize imported clean hydrogen and its derivatives to co-fire in existing coal power plants or new-build gas power plants.[165]

Other countries have begun implementing a variety of policy measures to help reduce risks in hydrogen project development, particularly in nations that anticipate becoming major producers and exporters of clean hydrogen. In Chile, which intends to become a leading producer and exporter of clean hydrogen in the future, the government awarded six projects a combined total of $50 million in grant funding in December 2021 to develop renewable hydrogen production projects.[166]

There has also been significant movement in India, where in 2023 the government approved nearly $2.2 billion for its Strategic Interventions for Green Hydrogen Transition program to build up domestic electrolyzer-based hydrogen production. This policy implements a competitive bidding scheme, with selected bidders receiving $0.23 to $0.36/kg H_2 as an additional incentive for production.[167] This would help the country reach its national hydrogen target to produce 5 MMt of green hydrogen annually by 2030. Also, the Indian government may soon release mandates for clean hydrogen end-use.[168]

Across the globe, multiple countries have opted to develop industrial hubs to scale up hydrogen production, transport, and end-use. In 2021, Australia's government provided grant funding across the clean hydrogen value chain, allocating nearly $349 million to support the country's Clean Hydrogen Industrial Hubs and approximately $9.4 million through its Advancing Hydrogen Fund to support fuel cell mining truck deployment.[169,170] More recently, the country's federal budget for 2023-2024 included the announcement of the Hydrogen Headstart Program to devote $1.4 billion to large-scale renewable hydrogen projects.[171]

In the UK, the Hydrogen Valley is an East-West corridor, encompassing Norfolk in the east and Shropshire in the West, intended to reduce CO_2 emissions by 12.9 MMt annually. The vision for the Hydrogen Valley was set by the House of Commons in March 2023 to attract up to 28 billion British pounds ($35.8 billion) in private capital investment in hydrogen production by developing a green economy in the region. The Hydrogen Valley is home to major operations in power generation, automotive, manufacturing, metal processing, and building materials. The project would safeguard and create 34,000 jobs in the region. The UK government has announced over 2 billion British pounds ($2.5 billion) for green hydrogen production projects to "make sure more of our energy is made at home in the UK."[172]

Similarly, Namibia set a target to produce 1 - 2 MMt of clean hydrogen annually by 2030 and increase its capacity by 10 MMt to 15 MMt by 2050. This would largely occur in its three planned hydrogen valleys where production and use can ramp up.[173]

The U.S. Regional Clean Hydrogen Hubs Program (H2Hubs) is another policy example of industrial clusters being used to reduce hydrogen project development risk. Through the enactment of the Bipartisan Infrastructure Law (BIL) in 2021, the H2Hub program has selected seven regional hubs located throughout the United States that have received a combined $7 billion to create local networks of producers, consumers, and connective infrastructure. Up to $1 billion in funding has been dedicated to implementing demand-side support mechanisms and further de-risking long-term hydrogen investments.[n]

Medium-Term Project Development (2030 to 2035)

While it is important to see how top-down policy actions at the national and international levels could impact global hydrogen market formation, it is also essential to acknowledge how the actual projects to produce and consume clean hydrogen within the coming decade are developing. Identifying these first-mover, or first-of-a-kind (FOAK), projects can give developers a more realistic assessment of where the market is moving.

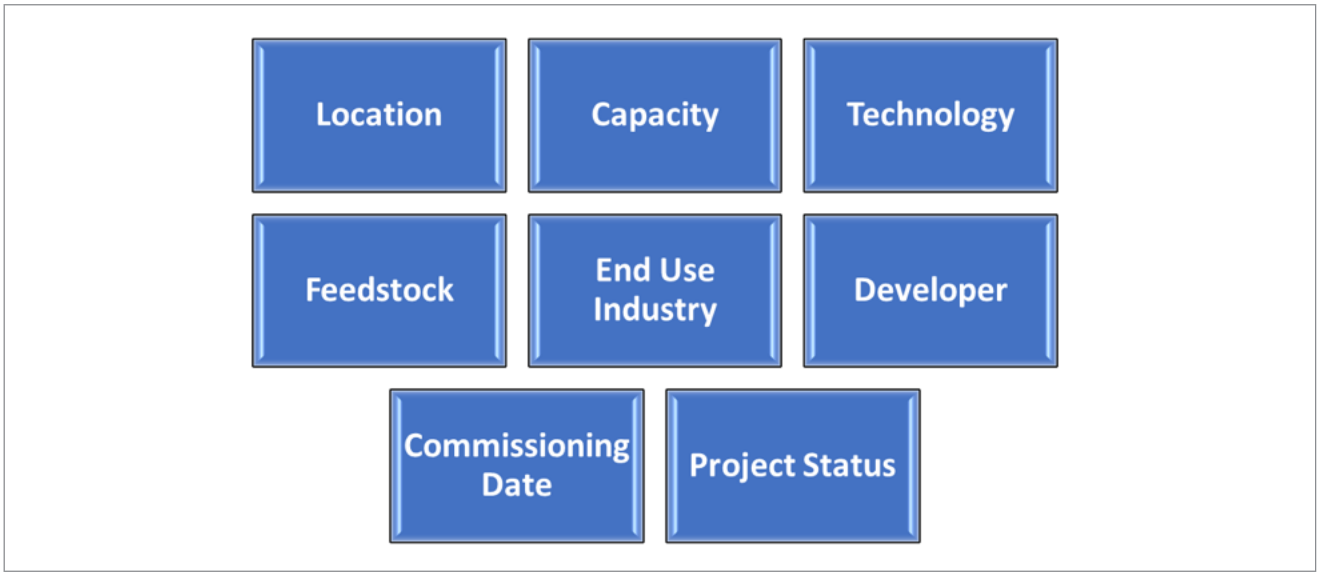
n In January 2024, the EFI Foundation was selected to lead the consortium to design and implement up to $1 billion demand-side support mechanisms for the H2Hubs program.

To build out this assessment, EFI developed an internal database that contains project-level data on almost 1,400 clean hydrogen projects across 56 nations. The database is compiled from various data sources, including IHS Markit, IEA, and Wood Mackenzie, as well as corporate and government announcements worldwide, to encompass a diverse set of data points that describe the nature of each project (see GEO Database appendix). In collaboration with KAPSARC and industry experts, EFI refined this database to categorize projects based on their likelihood of success roughly within the next decade (i.e., being constructed and operating in the 2030 to 2035 time frame). This analysis focused on eight definitional characteristics of projects that were compiled from a variety of public and proprietary data sources to better understand the nature of each project (Figure 18).

A multistep taxonomy was developed to list projects based on their realization potential. With these characteristics in mind, this analysis used a four-step process to assess each project's likelihood of success:

1. ***Operationality:*** Projects without defined commissioning dates were removed, as this indicates that a project is still in a conceptual

Figure 18. Project characteristics for hydrogen development database



Source: EFI, 2024

phase (i.e., aspirational) versus being in a development phase.

2. ***Capacity and developer:*** Experts and the joint team reviewed this list and eliminated projects that appeared unrealistic based on their size and developer profile.

3. ***Technology:*** Technologies deployed to produce clean hydrogen were reviewed, removing any with unmitigated (i.e., gray hydrogen) emissions. Projects with limited or uncertain technology options and evolving non-commercial technologies were removed.

4. ***End-use:*** Projects are categorized by their end-use industry, with metals, steel, refining, chemicals, transport, and ammonia projects retained as more likely to proceed. Other niche end-uses were screened out because of demand-market pull. An additional refinement was conducted to remove any projects for ammonia used for fertilizer production and refinery projects. This final filter reduced the number to 95 clean hydrogen projects as likely completed in the short term by the 2030 to 2035 time frame. (See appendix "The GH Project List – 4StepScreen Applied.")

> **A recommendation extending from this work is to establish data standardization and information sharing for a comprehensive source for a global hydrogen market.**

Additionally, this analysis tracks these project developments from countries with publicly available national hydrogen strategies (as of year-end 2023) to gain visibility into national priorities, deployment timelines, and policy mechanisms. For the most part, national hydrogen strategies indicate a willingness to adopt a regulatory framework that supports hydrogen development from a chemical good to an energy carrier. Bottom-up project developments combined with top-down strategies and policy mechanisms can facilitate the rapid scale-up of a global hydrogen market.

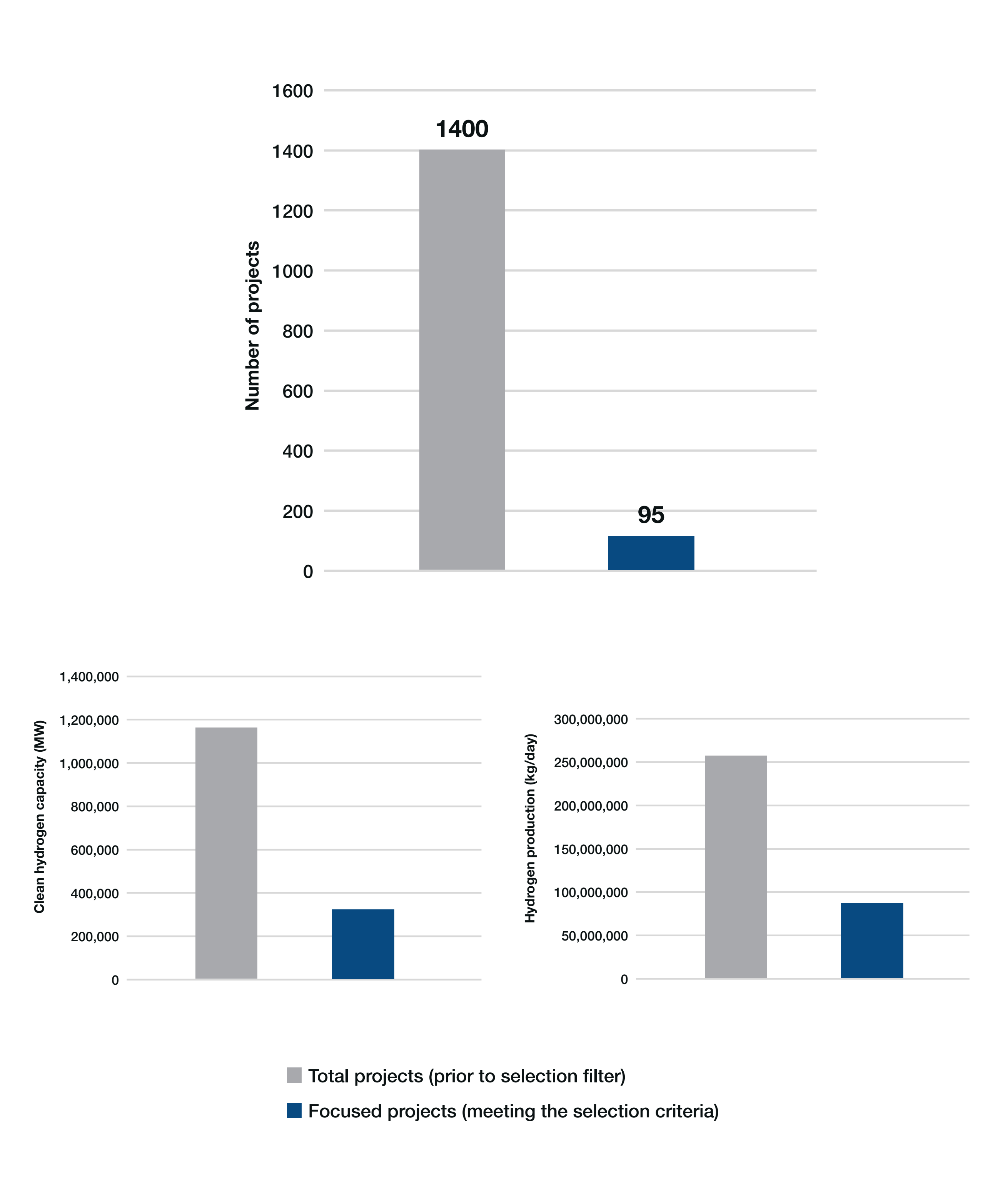
This type of criteria evaluation enables an outlook on the global hydrogen landscape that could serve as the foundation for predictive models and scenario analyses. Ultimately, using a more refined database as a "base case" could provide a more realistic view of potential clean hydrogen supply and demand for the coming decade. There are limitations, however, surrounding data availability and timeliness, subjectivity, simplification for modeling, bounded scenarios, forecasting uncertainty, geographic location, and end-use biases. Some degree of imprecision is unavoidable but can be mitigated through prudence and transparency in future data. A recommendation extending from this work is to establish data standardization and information sharing for a comprehensive source for a global hydrogen market.

Outcomes of Project Database Analysis

Utilizing the above criteria, an integrated analysis of the Global Hydrogen Database reveals several key insights as illustrated in this section and by Figures 19-25.

Based on announced projects globally, total clean hydrogen electrolyzer capacity could reach approximately 325 GW by 2035, and production of clean hydrogen could scale to approximately 88 MMt per year by 2035. Figure 19 accounts for the total number of operational projects and those in development globally. It also includes two charts on the projects' cumulative clean hydrogen capacity and production.

Figure 19. Announced projects by number, electrolyzer capacity, and production

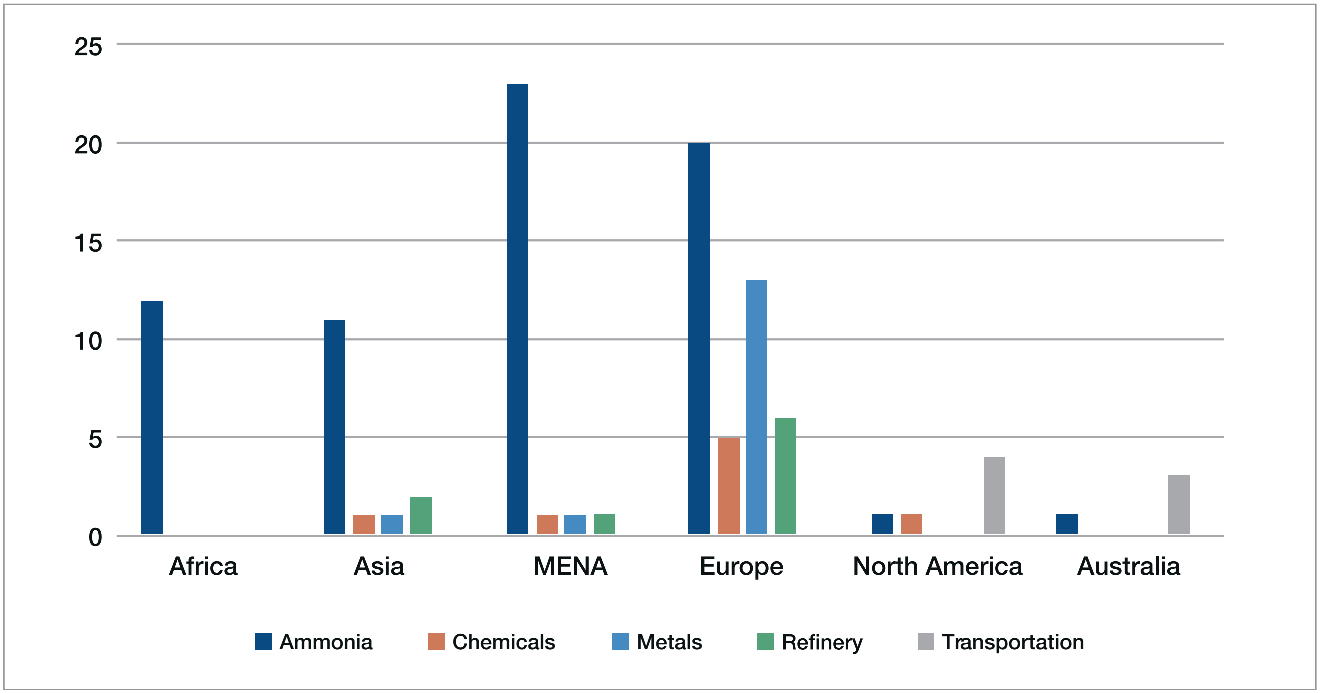


Source: EFI, 2024

However, applications in the chemicals, metals, ammonia, power generation, and transportation industries are forecast to constitute a growing share of demand capacity additions, reflecting sectoral diversification.

Today, refining applications account for over half of global hydrogen demand, mostly of gray hydrogen. The analysis suggests refineries could make up nearly 35 Mt of projected future production capacity by 2035. However, applications in the chemicals, metals, ammonia, power generation, and transportation industries are forecast to constitute a growing share of demand capacity additions, reflecting sectoral diversification. A regional comparison of aspirational projects for clean hydrogen shows a continued and expanded focus on ammonia production. Approximately 30% of all FID-phase clean hydrogen projects are in Europe, and commitments to clean hydrogen projects globally are for ammonia production. Of note, Figure 20 shows a commitment to clean ammonia production in Africa. Project announcements in South Africa highlight the great potential for a boost in low-carbon energy projects focused on clean hydrogen in developing African nations. As part of a movement to accelerate clean hydrogen as a key part of the future energy system, in November 2023, the World Bank, along with the Organization for Economic Co-operation and Development (OECD) and others, proposed an initiative for global deployment of clean hydrogen projects. This announcement of the initiative was followed by a report focused on scaling up hydrogen project financing for development, which is a good initial step to assist in financing, to de-risk projects, and to promote policies to boost demand.[174,175]

Figure 20. Number of announced projects across regions and industries through 2035



Source: EFI, 2023

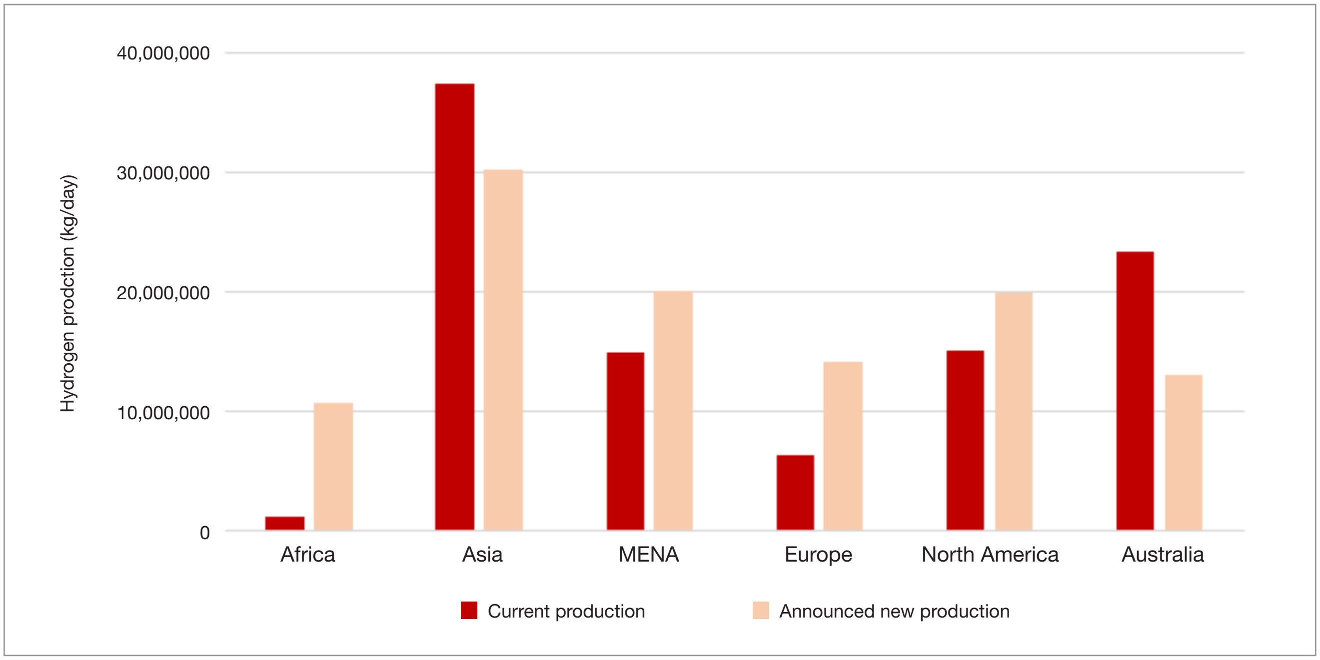
> **While Europe may lead in the total number of announced projects for all listed sector end-use ammonia, chemicals, metals, refining, and transportation by 2035, total capacity and hydrogen production will be higher in MENA and Asia, where fewer but larger projects for ammonia production have been announced.**

While Europe may lead in the total number of announced projects for all listed sector end-use ammonia, chemicals, metals, refining, and transportation by 2035, total capacity and hydrogen production will be higher in MENA and Asia, where fewer but larger projects for ammonia production have been announced. The NEOM Hydrogen project, which is expected to be the largest hydrogen manufacturing hub when commissioned in Saudi Arabia, is a good example of a large-scale development in MENA. Figure 21 shows the total production and capacity of the projects noted in Figure 20.

Asia currently leads in active projects, but announced capacities suggest significant geographic shifts by 2045. MENA region production is forecast to grow exponentially; however, China remains the largest clean hydrogen production and demand center. China leads production as well (Figure 22), albeit emissions-intensive gray hydrogen, with approximately 33 MMt H_2, or 30% of the world's hydrogen, produced in 2020.[176]

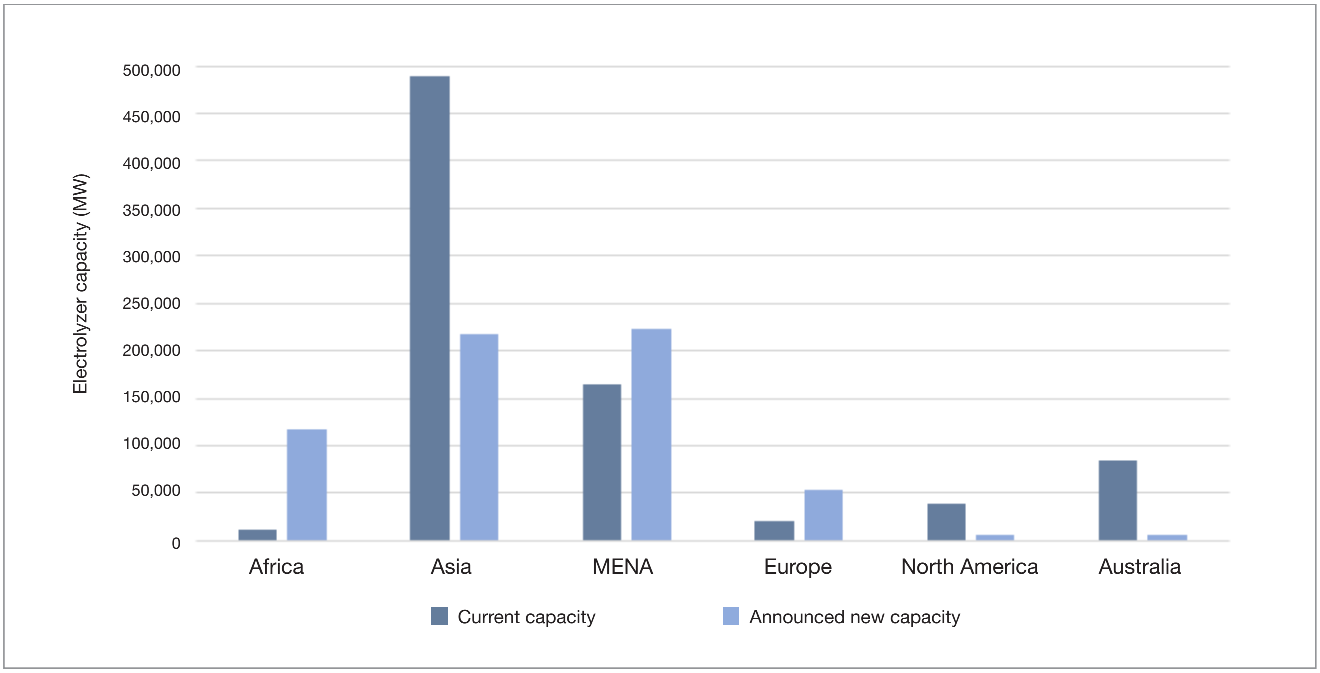
Europe, North America, and Africa are also poised for major clean hydrogen capacity growth. Currently, Australia is the leading exporter of hydrogen, specifically after it partnered with Japan

Figure 21. Contrast of current (gray) and announced (clean) hydrogen production regionally (kg H_2/day)



Source: EFI, 2024

Figure 22. Contrast of current and announced electrolyzer capacity regionally (MW)



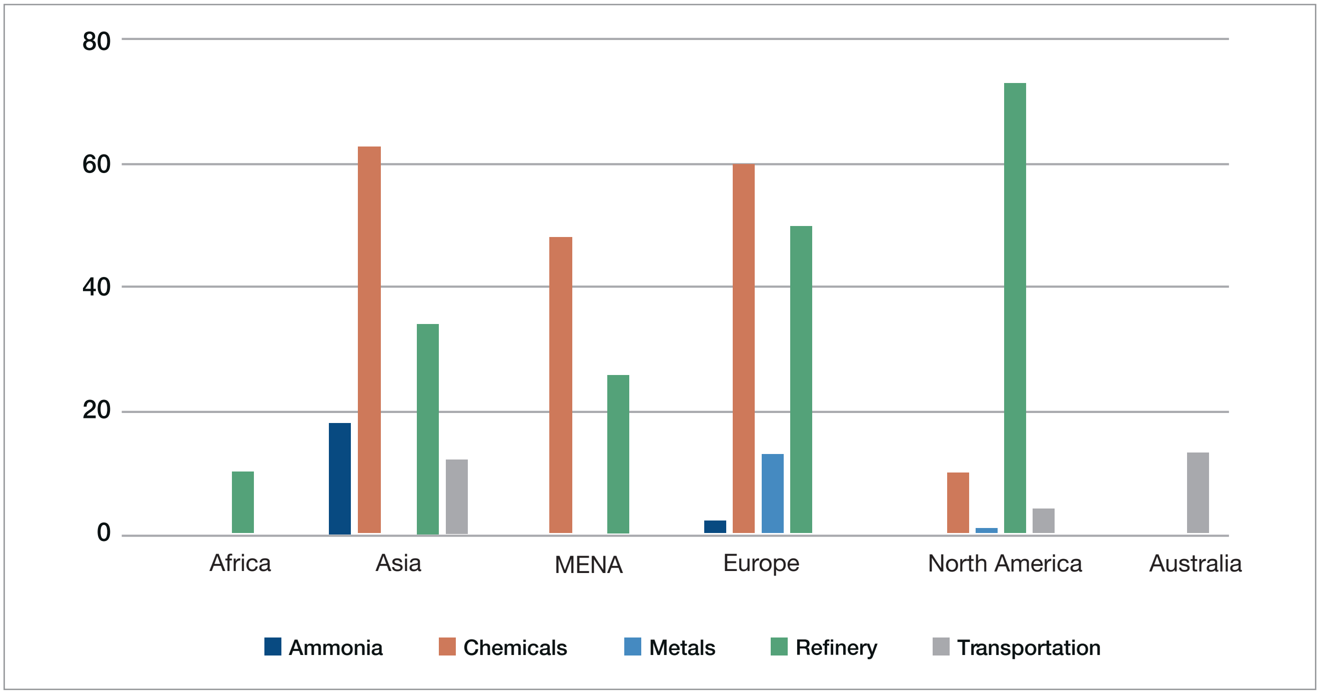
Source: EFI, 2024

on exports in the Japan-Australia Partnership on Decarbonization through Technology, which is part of the Australian Clean Hydrogen Trade Program.[177]

While Europe has the most projects in advanced planning and construction stages, North America has the greatest commitment to operational capacity. This may reflect North America's greater focus on producing high volumes of clean hydrogen for refineries and ammonia for fertilizers as replacement of gray hydrogen production for those industries. Europe's project funnel may face greater challenges progressing from announcements to operations. These challenges include limited infrastructure like pipelines to transport hydrogen; unclear regulations and policies for hydrogen crossing multiple countries; competition with other sectors for renewable electricity needed to produce green hydrogen; high costs of electrolyzers and renewables making hydrogen uncompetitive with fossil fuels; and lack of a distribution network to move hydrogen across Europe.

Figure 23 shows the differences in the number of projects across regions. Australia's small number is due to most of its projects being classified as export hubs, which were not included in this analysis but which will help make Australia a major exporter. As shown in the figure, the United States is developing 73 refinery projects. Australia will become a major exporter with most projectsclassified as export hubs. Europe, North America, and Asia are the largest hydrogen-producing regions by active projects.

Figure 23. Active projects compared across regions



Source: EFI, 2024

The data clearly shows increasing commitments and development in hydrogen globally. Five target subsectors—ammonia, chemicals, metals, refineries, and transportation—are expected to push growth over the next 10 to 12 years. EFI analyzed the growth of hydrogen capacity and hydrogen production (kg/day) for two milestone years, 2030 and 2035.

Capacity trends show a high growth curve for MENA and Asia between 2030 and 2035. MENA is expected to see a 43% rise in capacity in those five years. Saudi Arabia, the United Arab Emirates, and Oman are front-runners, with significant investments in ammonia production. Hydrogen export infrastructure capacity, which is not included in our database, could be added to the database to indicate which nations are investing in export infrastructure.

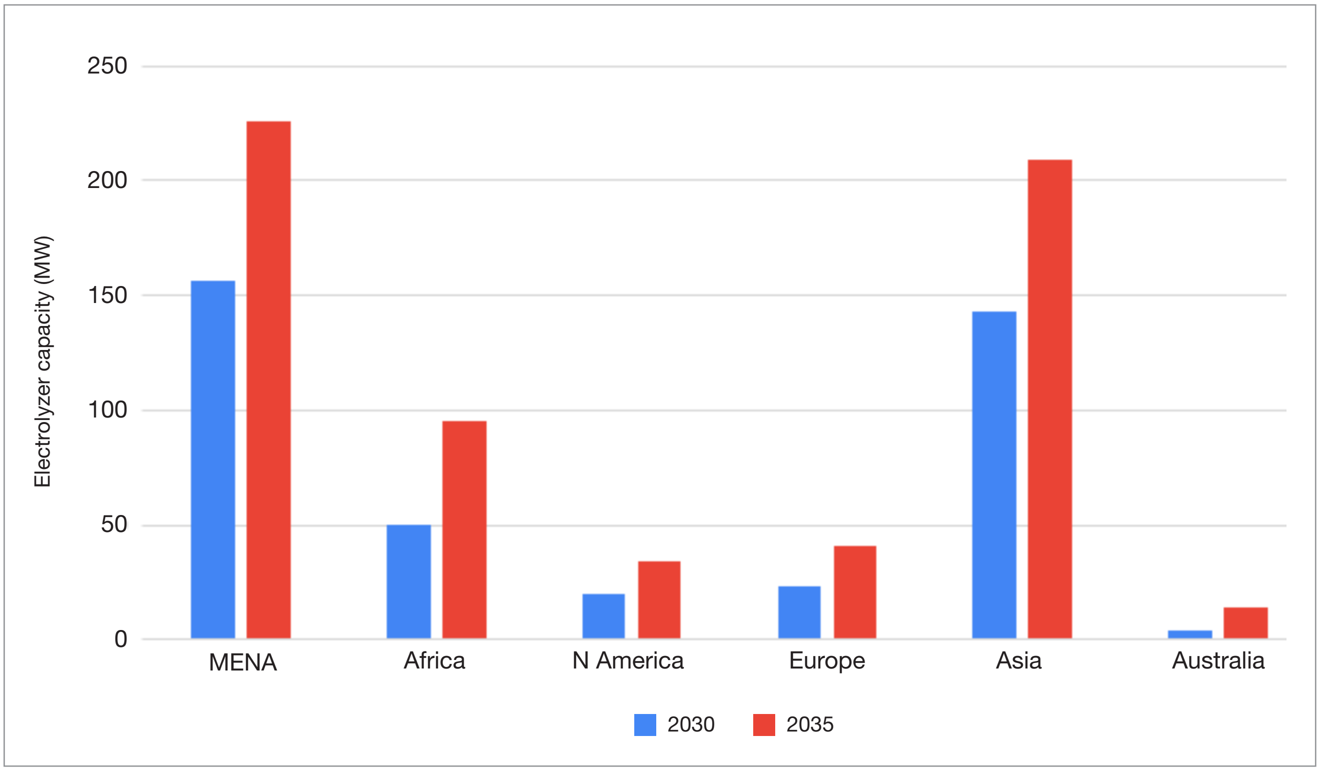
Using data from existing and announced projects, Figure 24 shows that the MENA and Asia regions are forecast to be leaders in hydrogen capacity by 2030 and 2035. While Europe currently has the highest number of announced projects committed to producing clean hydrogen, analysis of the data indicates a lack of confidence among past projects in getting to the FID stage. The four-step evaluation process of this data forecasts the Asia and MENA regions as having the highest probability of project success.[o]

Production of clean hydrogen is forecast to increase dramatically by 2035 (Figure 25). Asia is expected to produce a massive 28 million kg/year of hydrogen, which will be produced at large hubs in China and India. Considering the announced projects, India has made green ammonia production a high priority.[p]

o Given the Oct. 13, 2023, announcement of the U.S. Department of Energy's $7 billion in funding support for seven hydrogen hubs across the United States, the North American project data needs further refinement to reflect this once hub contracts are finalized in coming years. This information is significant because the hub proposals will constitute the greatest volume of incremental clean hydrogen production in North America. Projects that made it through the four-step screening process are listed in the "Projects" attachment.

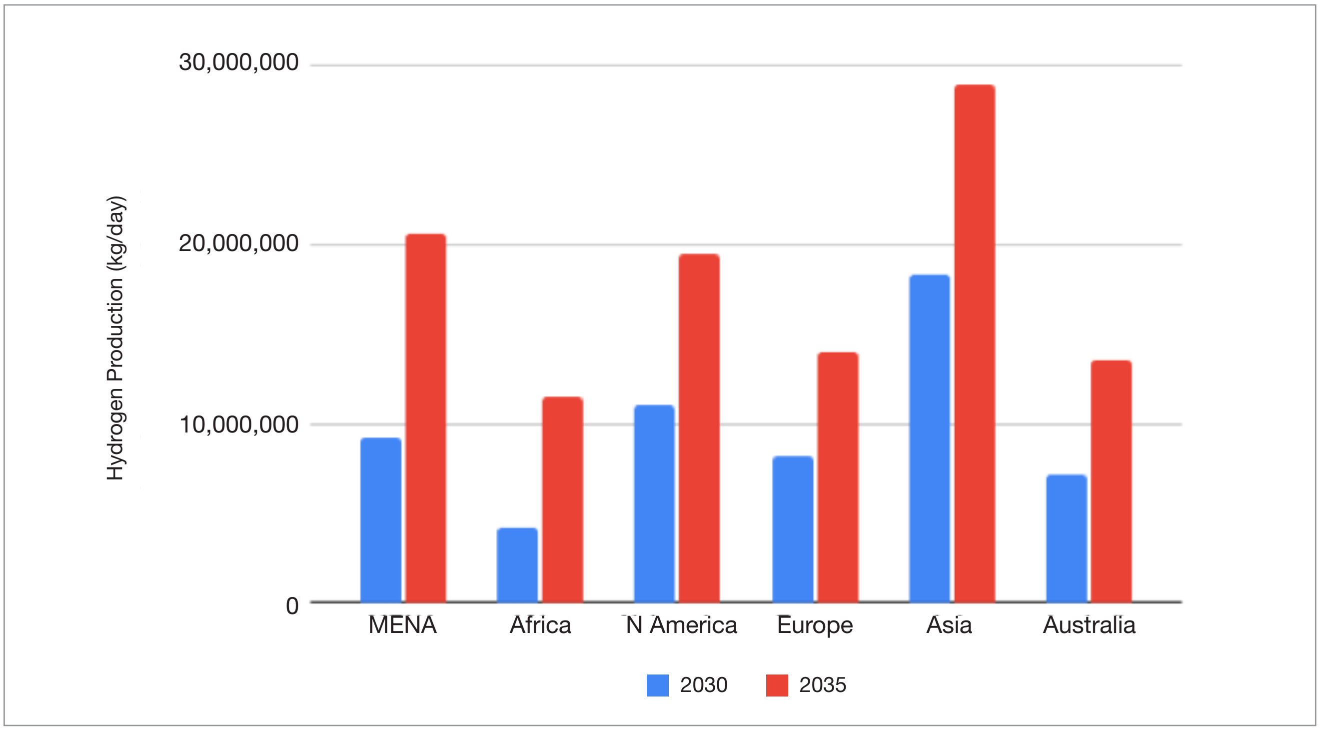
p India has committed to adding 5.8 million metric tons of green ammonia manufacturing capacity, according to the country's Ministry of New and Renewable Energy.

Figure 24. Total project capacity forecast from the 2030 base case and 2035



Source: EFI, 2024

Figure 25. Hydrogen production forecast for 2030 base case and 2035



Source: EFI, 2024

The hydrogen economy exhibits tremendous potential for rapid growth in the coming decades. Realizing this potential will require accelerating project maturity, supplying vital infrastructure, stimulating sector coupling (i.e., transfer of energy to other sectors, where it is used to reduce the use of fossil fuels), and facilitating global collaboration. These findings are a result of an evaluation process that placed a high degree of expected success on the 95 projects that made it through the four-step evaluation process.

This analysis reveals that clean hydrogen will expand rapidly, even in the short term, with total capacity potentially exceeding 500 GW and production reaching 76 million metric tons annually by 2035. Analysis of the database shows that, while the replacement of gray hydrogen in the refining, chemicals, and fertilizer industries may drive near-term demand in many regions, demand from metals, cement, power generation, and transportation will grow as new demand sources in others. Regional dynamics are also set to shift, with MENA emerging as a major production hub and China dominating as a production and demand center.

> **By 2035, capacity is expected to increase by 285 MW for these subsectors, which is an expected increase of 117% in just 11 years.**

Currently, in just the five target hydrogen-demand subsectors (metals, refining, chemicals, transportation, and ammonia) existing capacity is approximately 243 MW. By 2035, capacity is expected to increase by 285 MW for these subsectors, which is an expected increase of 117% in just 11 years. Realizing hydrogen's full potential, however, requires overcoming key challenges, and project maturity remains uneven globally, with many of the aspirational announcements yet to reach a viable stage of development.

This integrated methodology combining quantitative and qualitative inputs provides unique visibility into the complex and rapidly changing hydrogen landscape. As the industry matures, maintaining this dynamic database will grow increasingly vital. The database is a baseline for scenario development or verification of projected hydrogen growth. Using the Global Hydrogen Database (GEO Database), which encompasses granular data on almost 1,400 projects worldwide combined with methodical filtration, can provide a realistic baseline outlook on potential hydrogen supply and demand growth over the coming decades.

Regional Insights

The insights from the project database can inform case studies to provide a bottom-up perspective on regional market development. For example, the database shows a gap in project development despite policy movement in key European markets. The H2Global initiative in Europe, led by Germany and the Netherlands, uses a double-auction mechanism where an intermediary functions as a dedicated offtake vehicle that then sets direct, contractual agreements with producers and consumers of hydrogen. This intermediary absorbs existing regulatory uncertainties and creates a more welcoming investment environment. So far, the initiative received a commitment from the German government of 4.9 billion euros ($5.2 billion) in 2023 that built upon its original commitment of about 900 million euros ($1.1 billion). The Netherlands has also joined the initiative and dedicated around 300 million euros ($400 million). These funds will be used to make up the difference in cost between the hydrogen-based fuels auctioned through H2Global and the current cost of unabated fossil fuel-based hydrogen. The bidding process of the auction began in 2022, and deliveries of hydrogen were originally expected around the end of 2024. Bid tender deadlines have been recently extended and could shift these deliveries to 2025 (Figure 26).[178,179]

Figure 26. Overview of the H2Global Initiative

Source: Hydrogen Intermediary Network Company (Hintco), "The H2Global Instrument," accessed March 5, 2024, https://h2-global.de/project/h2g-mechanism.

The project database, after application of the four-step screening process, found about 17 hydrogen production projects at FID or under construction in Germany that will come online within the next decade. Together, these projects are forecast to produce nearly 1.4 MMt H_2/yr by 2040 and are largely utilizing electrolysis-based production pathways. Nearly all of these projects are being developed by German companies, but it remains unclear where the demand for this hydrogen will come from. While there are announced electrolysis projects located in the Netherlands—and the country is expected to contribute to European production—the screening of the project database found these projects were still mostly in early development stages. To put this in perspective, Europe has announced intentions to reach a total supply volume of almost 14 MMt H_2/yr by 2030.[180] The Netherlands is already the second-largest global importer of hydrogen, and Germany is expected to be one of the largest importers in the future based on its demand expectations over the coming decades.[181]

Box 3 in Chapter 2 contains a regional case study from the project database looking at the impact of policy and trade agreements between Japan and Australia to bridge future clean hydrogen supply with demand. The database identifies at least four publicly announced trade agreements signed between Japanese and Australian companies, with five additional agreements supplying Australian clean hydrogen to other East Asian and Pacific Island countries. Based on publicly available data, these agreements already surpass $80 million in private investment.

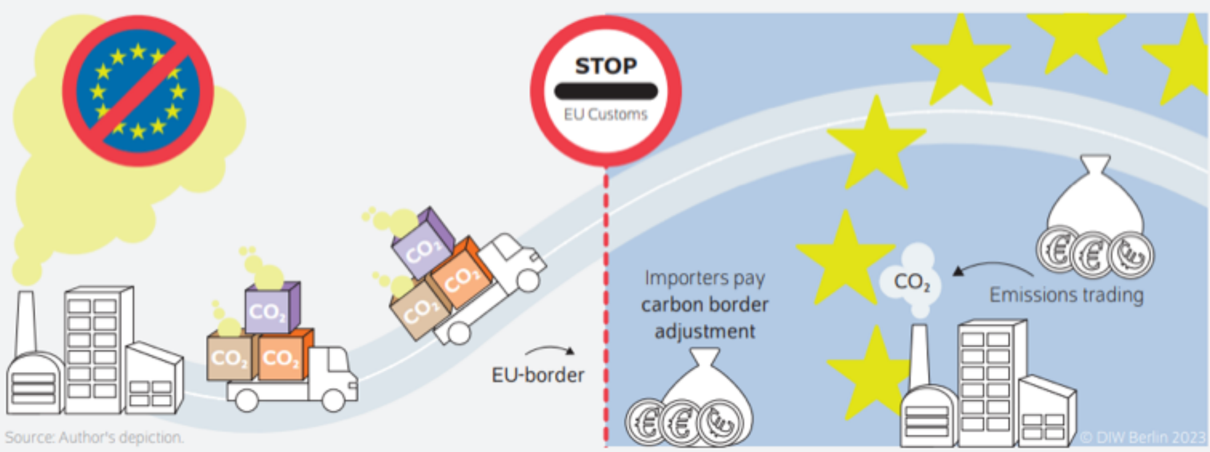
International Regulations and Gaps

The global hydrogen market will require greater international coherence on national strategies and international regulations (MENA workshop). Focusing on climate regulations across the globe, the European Union's Carbon Border Adjustment Mechanism (CBAM) (Box 5) and its "Fit for 55" package as part of RePowerEU are important regulations to spur investment, primarily through emissions reduction and infrastructure uptake requirements. Still, there is a significant gap among European countries between anticipated hydrogen production and consumption, which could amount to 1.8 MMt by 2030. This gap, most evident in countries like Germany, represents the best opportunity for hydrogen imports, particularly from the MENA region.

Box 5. The EU Carbon Border Adjustment Mechanism (CBAM)

The EU's CBAM is one of several tax and carbon price reforms initiated as part of the EU Green Deal to level the playing field so domestic industries can compete with goods produced abroad with more emissions-intensive fuels. This mechanism is also meant to reduce "carbon leakage"—a phenomenon whereby companies move operations offshore to avoid the costs of complying with stringent domestic environmental standards or import foreign products that are not subject to a carbon tax in the country of origin (Figure 27).[182] Exporters to the EU must either pay an import tariff on carbon-intensive goods or meet emissions requirements by upgrading their infrastructure or switching to lower-emissions fuels such as green hydrogen. The near-term lack of supply of such lower-emissions fuels could create price volatility as supply catches up with demand. This could also impact the cost and availability of critical goods necessary to meet the infrastructure needs of the energy transition.

The EU's Carbon Border Adjustment Mechanism: Preventing carbon leakage



Source: DIW Weekly Report 22/2023, Robin Sogalia, The New European Carbon border Adjustment Mechanism, https://www.diw.de/documents/publikationen/73/diw_01.c.873991.de/dwr-23-22-1.pdf.

As of today, the implications of the CBAM remain unclear. The policy is intended to enable a resurgence in European industries and ensure that imports of listed products are consistent with low-carbon manufacturing technologies.

Applicable regulations exist today to spur initial hydrogen development; however, more regulation is needed on the demand side to enable the true market potential of hydrogen as an energy commodity (U.S. workshop).

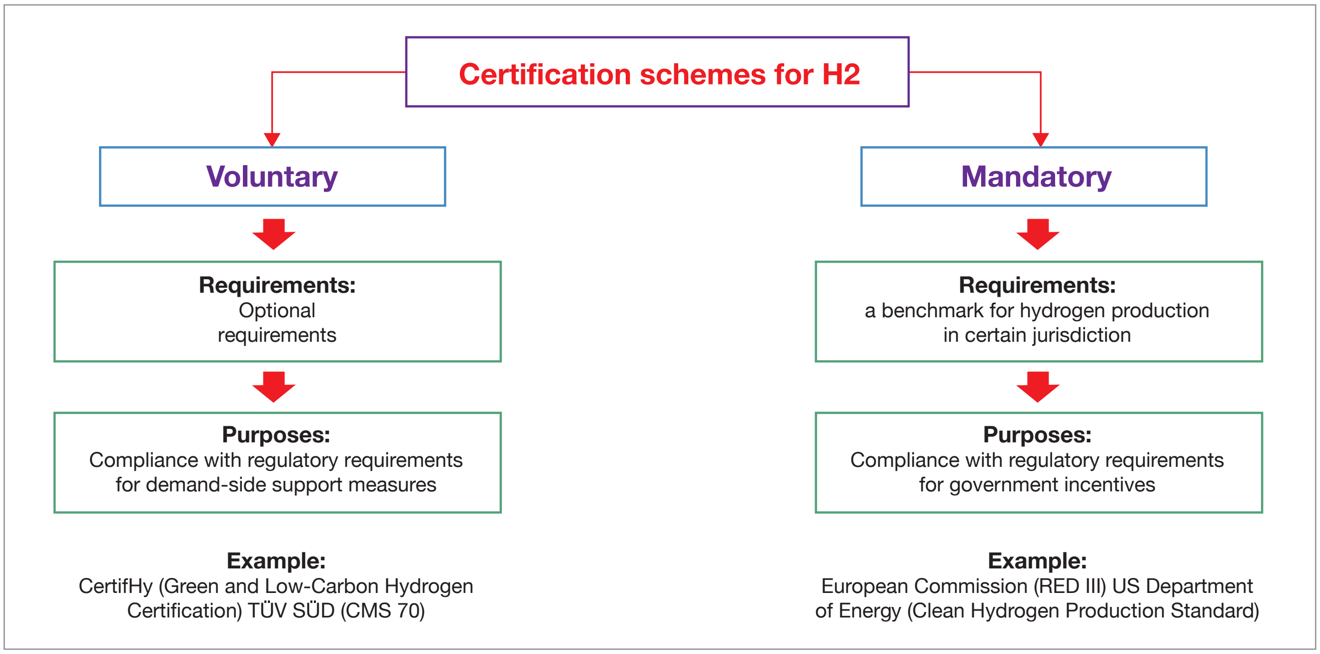
Applicable regulations exist today to spur initial hydrogen development; however, more regulation is needed on the demand side to enable the true market potential of hydrogen as an energy commodity (U.S. workshop). Current hydrogen regulations are inadequate because they are largely confined to safety regulations regarding hydrogen's role as a specialty chemical. As is the case in the United States, current regulations for hydrogen occur at both the federal and state levels. The U.S. Occupational Safety and Health Administration (OSHA) treats hydrogen as a hazardous material and ensures its safe production, transport, and use.[183]

If the hydrogen is to be transported via pipeline, a variety of federal and state agencies have overlapping jurisdiction to regulate the economic, safety, siting, and environmental protection components of pipeline development. While there are aspects of these regulations that could help inform the safe trade of hydrogen internationally, the overlapping jurisdictions of these agencies create much slower permitting timelines for hydrogen development.[184] In order for global market formation to progress, regulations must also view hydrogen as an energy commodity and energy carrier, and ensure its safe production, transport, and distribution without slowing market growth.

Certification Schemes

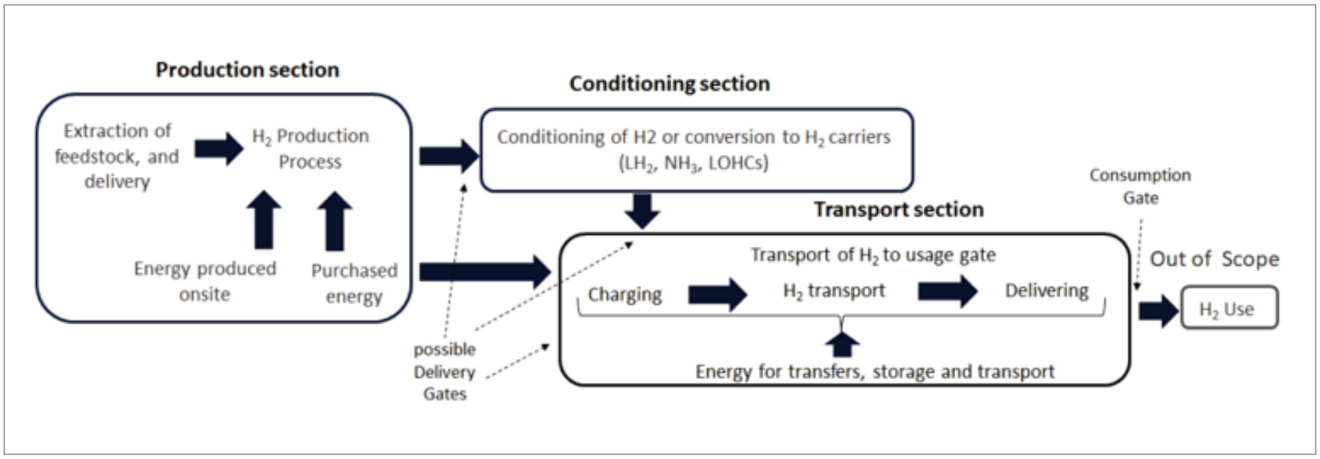
The main concern for hydrogen certification is the embodied carbon intensity in its production and transport. Such certifications could follow voluntary or regulatory frameworks (Figure 27). Regardless, a certification that specifies a value for embodied carbon is essential for a globally acknowledged standard.

Figure 27. Overview of different types of certification schemes for hydrogen



Source: Hydrogenious, 2023, https://www.certifhy.eu/.

Figure 28. 'Well-to-gate' system boundary divided into three sections (production, conditioning, and transport)



Source: International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) Hydrogen Production Analysis Task Force, Methodology for Determining the Greenhouse Gas Emissions Associated with the Production of Hydrogen, July 2023, p. 39, https://www.iphe.net/_files/ugd/45185a_8f9608847cbe46c88c319a75bb85f436.pdf.

The versatility and flexibility of hydrogen as a fuel and feedstock, related to the differences in production methods and uses, make carbon intensity calculations particularly challenging. The complexity lies in the fact that there are many life cycle assessment (LCA) methodologies to calculate GHG emissions across product supply chains. The challenge is which LCA methodology is adopted in the calculation and what are the boundary conditions (e.g. well-to-gate, gate-to-gate, cradle-to-cradle, etc.). As things currently stand, each country/region is coming up with its own interpretation of both LCA and non-LCA-related attributes. The ISO/TS 19870:2023[q] LCA Methodology for hydrogen released at the United Nations Climate Change Conference COP28 is an attempt to act as general guidance and potentially create a standard approach to calculating GHG emissions. It is based on the methodology of the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE). These certification schemes will also need to address the cost and embodied carbon of the additional infrastructure buildout required, such as plant construction, CCUS, and hydrogen pipelines, among other supporting nfrastructure.

As noted, the IPHE, recognizing these various pathways for embodied emissions in hydrogen production and transport, has led the development and refinement of a carbon intensity calculation methodology. The IPHE uses a "well-to-gate"[r] boundary, meaning that the production, conditioning, and transport of hydrogen—as well as its derivatives such as ammonia or methanol—are evaluated to estimate a value for a particular production pathway's embodied carbon (Figure 28).[185] This version of the methodology is the first to incorporate hydrogen transport carbon intensity calculations.

q For details on this guidance from the International Organization for Standards (ISO): https://www.iso.org/standard/65628.html

r IPHE defines "well-to-gate" system boundary implying that all GHG emissions are being considered—upstream, during production, distribution, and storage of hydrogen. https://ptx-hub.org/wp-content/uploads/2023/08/International-PtX-Hub_202308_IPHE-methodology-electrolysis.pdf

Another major area of concern is varying levels of acceptability of hydrogen sourcing based on region, i.e., non-LCA attributes, which may not always directly correlate to carbon intensity. Nuclear power-sourced hydrogen may be low carbon, but in countries like Germany, where nuclear power is being phased out because of opposition, hydrogen produced from nuclear power might also be subject to controversy. Elsewhere in the EU may be a different matter, as the EU has classified nuclear power, under certain conditions, as a "green" source of energy.[186]

Verifiability is a strong concern as well. Trust among producers is always a tenuous balance, and when these relationships cross borders and oceans, it can be difficult for methodologies to be applied equally to, for example, hydrogen produced in Texas versus Australia versus China. Global bodies monitoring emissions by sector and certifying by sector have been relatively successful, and a global certification standard will need some mandate from a trusted independent body.

Balancing verifiable certification and regulatory burden will also be critical. Currently, the less embodied carbon that is in a unit of hydrogen, the greater the cost is likely to be. Quantifying and verifying the exact amount of embodied carbon is both nontrivial and introduces at least some small additional cost burden for the producer. Producers naturally do not want to increase their costs unnecessarily, so it is key that the demand-side policy creates a clear, reasonable standard that is followed consistently. Doing so will create an equal playing field for producers, so they are not handicapping their market position by following rules. An international agreement or governing body would be a useful facilitator, such as the International Organization for Standards (ISO), which has a history of setting standards across industries.

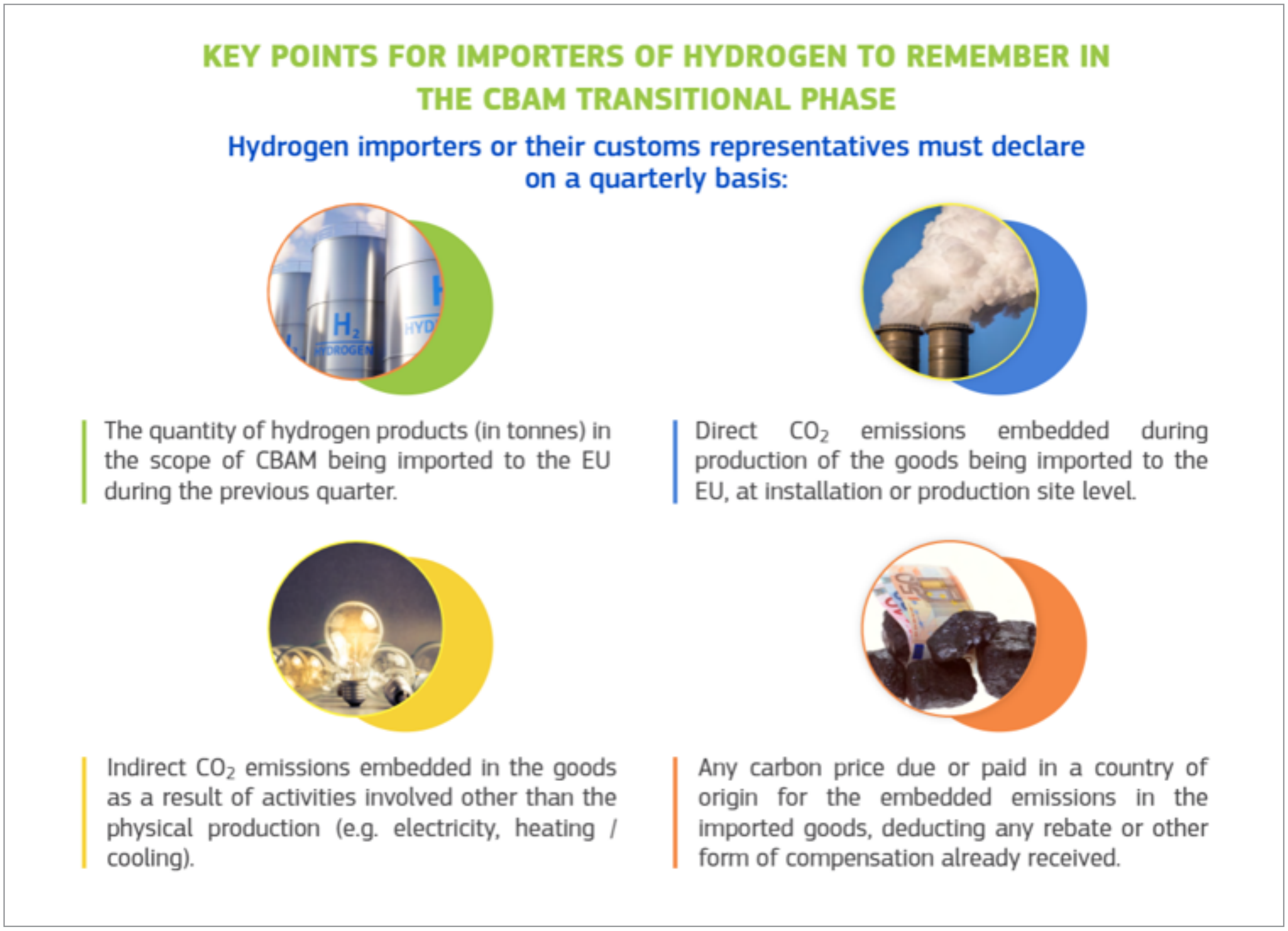
Currently, the EU's CBAM is in its "transitional phase" where, from 2023 to 2026, the mechanism gradually phases in to allow for a "predictable and proportionate transition" for companies operating inside and outside of the EU—thus some reporting on embedded emissions data became mandatory in 2024, with noncompliance fines set to start in July 2024.[187] Importantly, this period will function as a pilot to share lessons learned across importers, producers, and authorities on the embedded emissions for traded goods that will inform the "definitive" period that is set to begin after 2026 (Figure 29).[188] As such, importers will only need to report the GHG emissions embedded in their imports without buying or surrendering certificates.

Within the transitional phase, the CBAM applies only to highly emissions-intensive imported goods that are at a high risk of carbon leakage.[189] Carbon leakage can occur if—because of strict climate-related regulations in a particular country or region—businesses transfer production to other countries with more relaxed emission constraints and ultimately increase emissions.[190] The industries at risk of carbon leakage and currently under regulation by the CBAM include cement, iron and steel, aluminum, fertilizers, electricity, and hydrogen.[191]

There is also an element of realism that must be included in these goals. Fully decarbonized energy production is rare and expensive in a world that uses so much fossil fuel. It is easy to say that because you used an electrolyzer and solar panels you have a completely carbon-free source of energy, but the carbon involved in the capital expenditure and the leakage that can result from pulling so much renewable energy from the grid all must be considered. This full value chain accounting is key to ensuring that quantifiable decarbonization is achieved.

Global certification that gives a clear answer on how much carbon intensity is embodied in the production and transport processes will be key to building a global commodity market. The methodology proposed by the IPHE is robust and accurate, and the partnership seems well positioned to continue to update that policy.

Figure 29. Hydrogen-related declarations required to qualify for the EU's CBAM



Source: European Commission, "Carbon Border Adjustment Mechanism," accessed March 8, 2024, https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en.

If a standardized process can be developed for producers to certify the carbon intensity of their produced hydrogen, consumers can make informed choices that feed into their regulatory and voluntary market frameworks.

Without a method that can be replicated and trusted, consumers will continue to rely on bilateral agreements for global hydrogen trade, which could fracture a global hydrogen commodity market. This will be a missed opportunity, preventing appropriate price formation and market growth. From the demand-side perspective, potential importers of hydrogen should be proactive in developing global certification frameworks that will be acceptable and useful to all major importers.

Ammonia Regulations and Certification

The regulation of ammonia across international borders encompasses various facets, addressing its use as a fuel and a fertilizer, and ensuring safe handling to mitigate health and environmental risks. Here is an integrated narrative outlining the international regulatory landscape concerning ammonia:

1. ***Usage of ammonia in renewable energy and fertilizer industries:*** Ammonia's crucial role as a base for mineral nitrogen fertilizers and a potential zero-carbon fuel is being acknowledged globally. Regulatory changes are underway to promote green ammonia production, aimed at decarbonizing

multiple sectors, including agriculture and transportation.[192,193,194]

2. ***Regulatory framework in the European Union and United States:*** The EU and U.S. are spearheading regulatory frameworks to transition toward low-carbon ammonia. While the EU's CBAM and Renewable Energy Directive (RED III) set emissions standards and green ammonia production targets, the United States is leveraging subsidies through the Inflation Reduction Act to promote green hydrogen and ammonia production.[195]

3. ***Market mechanisms and technology diversification:*** Market-based mechanisms like subsidies and contracts for differences are envisioned to reduce the cost premium for zero- or low-emission ammonia. Diversification in ammonia production technologies is being encouraged, as seen in the U.S. Department of Energy's Advanced Research Projects Agency-Energy funding initiatives for sustainable ammonia production technologies.[196,197]

4. ***Safe handling and storage of ammonia:*** International and national standards dictate the safe handling, storage, and usage of ammonia to mitigate its hazardous nature. In the United States, OSHA and the Environmental Protection Agency provide guidelines and standards for safe ammonia storage, handling, and refrigeration . Similar regulations exist in Australia, the EU, China, and India, each with its set of guidelines and standards, like the EU's EN 378 for safety and environmental requirements of refrigerating systems and Australia's Work Health Safety Act focusing on safe ammonia handling, among others.[198,199,200]

5. ***International maritime regulations:*** On the maritime front, the Det Norske Veritas (DNV) class rules for ammonia as ship fuel were introduced to pave the way for safe storage, handling, and bunkering of ammonia on board ships, addressing toxicity concerns and ensuring safety in maritime transport.[201]

6. ***Emerging regulatory trends:*** Countries like India and China are setting forth regulations to promote renewable ammonia production and ensure safe handling. For instance, India's draft hydrogen strategy sets renewable ammonia production targets for its domestic fertilizer sector.[202]

The evolving regulatory framework for ammonia, both as a fuel and fertilizer, reflects a global endeavor to leverage its potential sustainably and safely. This includes setting forth green production targets, ensuring safe handling protocols, and fostering technology diversification to meet the growing demand for ammonia in renewable energy and agriculture sectors.

Methanol Regulations and Certification

The regulation of methanol, with a focus on its potential as a fuel and a carrier for hydrogen, encompasses several dimensions, including its use in the maritime and automotive sectors as well as its role in facilitating the transition to cleaner fuels. Here's a comprehensive discussion based on various sources:

1. ***Methanol in the maritime sector:*** The maritime industry has shown interest in methanol as a potential alternative fuel, with ship owners, shipyards, and fuel suppliers expressing interest in methanol-fueled vessels. The International Maritime Organization has drafted interim guidelines for ships using methanol as fuel, and these guidelines, along with DNV's mandatory class rules for methanol-powered ships, pave the way for investments in methanol-fueled ships.[203,204]

2. ***Regulatory framework and safety considerations:*** The maritime sector awaits the final regulatory framework to commit to large-scale investments in methanol-fueled vessels. DNV has been proactive in publishing class rules on low-flashpoint liquid fuels covering methanol, addressing key concerns about its toxicity. Methanol's toxicity has previously been a point of opposition, but it has been handled safely as a seaborne

chemical commodity for more than 50 years, and the loading and unloading of methanol are considered less complicated compared with other fuels like ammonia.[205]

The evolving landscape of methanol regulation and its increasing recognition as a potential fuel and hydrogen carrier underline a global endeavor toward cleaner and more sustainable fuel alternatives. The maritime sector in particular emerges as a significant domain where methanol's potential is being explored, driven by a collaborative effort among stakeholders to establish a conducive regulatory framework and to address safety and environmental concerns.

Global data standardization applied on a regional basis is essential for hydrogen market development (U.S. workshop). Importantly, data sharing helps create transparency, supporting market certainty. The Joint Organization Data Initiative—a comprehensive database of energy statistics for oil and gas markets using nationally sanctioned data to create fair assessments of monthly production and consumption globally—could serve as a template for such data sharing.[206] This commonly accessible assessment would not only build greater transparency into a global hydrogen market but also help mitigate price fluctuations and facilitate greater producer-consumer dialogue.

Stakeholders have also emphasized the need for a common definition of clean hydrogen as essential to global market standardization. Policymakers should focus on carbon intensity definitions that would then offer clarity for other hydrogen regulations. However, it is also important to acknowledge that carbon intensity will fluctuate globally by region and subsequent definitions of clean hydrogen must also acknowledge those regional variations.

Policy Barriers and Discussion of Potential Solutions

There is still much debate surrounding the need for policy intervention and which policies can best facilitate global hydrogen market development (MENA workshop). From an industry perspective, including both carrots (i.e., the U.S. Inflation Reduction Act of 2022) and sticks (i.e., the EU’s CBAM) can create confusion for project developers and offtakers. The NEOM project in Saudi Arabia is an example of an offtake agreement that has recently moved forward without a government policy. One of the project developers (Air Products) backstopped the offtake agreement to satisfy project lenders,[207] highlighting the importance of regional context to inform how government intervention could impact movement on hydrogen.

In contrast, the other side of the debate views the problem to be too large for the private sector to solve alone. While industry players are progressing, the broader market has yet to find a “scalable, replicable business model.” Offtake still depends on policy guidance, and many stakeholders believe that governments need to do more to move hydrogen beyond the “searching phase” to create the needed exponential growth for hydrogen market development. However, the best type of government intervention remains unclear.

While subsidies can create demand for hydrogen, many developers have indicated a preference for greater regulatory guidance at this stage in market development (MENA workshop). In this context, it is important to offer clarifying definitions for policy and regulation. Policy describes the direction countries intend to go on hydrogen, and regulation represents a necessary framework of “rules of the road” to guide private investments. Subsidizing hydrogen in the same fashion as renewable energy likely will not work, largely because renewable demand from the grid already exists. Within the MENA region, none of the policies subsidize supply or demand. Additionally, the growth of solar and wind energy in MENA came from top-down government procurement. With hydrogen, the industry still needs to establish production sources, end-users, a competitive market, and connective infrastructure.

However, some industry stakeholders support hydrogen subsidies broadly because demand creation is intrinsically tied to cost competitiveness versus alternatives and incentives to reduce the overall cost of hydrogen production. In both the United States and Canada, incentives such as the U.S. 45V hydrogen production tax credit and Canadian clean hydrogen investment credit, respectively, can help provide medium- to long-term stability across the value chain while more directly reducing capital expenditures and bolstering production.[208] These subsidies can build upon the fact that there is already demand for hydrogen today that can easily be decarbonized, and some regulations already exist but tend to treat hydrogen as a specialty chemical. Regardless of the policy used to incentivize hydrogen value chains, developers and industry representatives have indicated that they need regulatory certainty to invest.

Beyond subsidies, carbon pricing mechanisms could encourage a global hydrogen market, but it will ultimately come down to price reduction (MENA workshop). Proponents of a carbon price have emphasized how it would level the technological playing field and encourage the best decarbonization options. Given the large volume of hydrogen imports expected for Europe, the EU's CBAM will likely drive hydrogen prices globally. In essence, this policy would globalize carbon emissions pricing, whether directly or indirectly (e.g., cap and trade).

Other industry stakeholders feel that carbon pricing is a nonstarter globally and policy should instead focus on properly implemented quotas, which they view as a more bankable policy solution. Ultimately, it will all come down to cost. Many developers have noticed a large discrepancy between the duration of long-term offtake agreements and price, which they attribute to unrealistic expectations for green hydrogen prices or products/derivatives. While most attendees agreed electrolyzer costs would decrease, they also acknowledged the importance of setting realistic expectations around how much technological innovation can reduce costs. It is still important to produce a cost-competitive product based on where hydrogen demand is today.

Different regions across the globe could benefit from well-designed public-private partnerships (PPP) that utilize the resources of national governments without stifling market-based innovation (MENA workshop). Industry participants highlighted some concerns about governments crowding out the private sector, particularly in the MENA region. To combat this, national companies could focus their resources on hydrogen produced via steam methane reformation (SMR) with CCUS in the near term to give space for the private sector to bring the costs down for electrolytic hydrogen longer term.

Some industry players in the region see the role of state-owned enterprises as one of MENA's primary advantages for rapidly scaling up its hydrogen industry. They also cited the potential for MENA governments to structure incentives for both production and demand in the form of equity grants and loan guarantees for production, and contracts for differences (CfDs) for both production and demand, among other support mechanisms. These stakeholders also encouraged MENA governments to consider instituting cap-and-trade markets to respond to carbon border adjustments and decarbonize domestic industries and supply chains. In Saudi Arabia, nearly 30% of the country's gross domestic product goes to government spending, and the state manages one of the largest sovereign wealth funds (SWFs) in the world. SWFs can play an important role in bringing green technologies to market given their longer time horizons. The Saudi Arabian SWF plans to champion PPPs to take on the risk of early technology adoption.

SWFs elsewhere are also promoting large-scale hydrogen development, especially as a mechanism to support deployment in the developing world. In 2023, Namibia partnered with state-supported firms from the Netherlands to develop SDG Namibia One, a $1.1 billion blended financing vehicle for green hydrogen investment in Namibia. This will allow the government of Namibia to acquire a 24% equity stake in the first green hydrogen project chosen to become the first fully vertically integrated gigawatt-scale project in the country to ultimately produce green ammonia around 2028.[209]

More broadly, global-scale interactions are taking form to mobilize funds for clean hydrogen. The Hydrogen Council—representing a global coalition of CEOs—has teamed up with the One Planet Sovereign Wealth Funds (OPSWF) Network to drive alignment around sustainability standards and certification solutions to boost global hydrogen trade and project execution. This coalition also has a strong focus on unlocking environmental and socioeconomic benefits in emerging and developing countries entering the hydrogen economy. Together, this group has nearly $50 trillion in assets, market capitalization, and revenues at its disposal.[210]

Midstream transportation challenges must be resolved to facilitate the development of a global hydrogen market (U.S. workshop). As discussed in Chapter 2, the transport of liquid hydrogen—whether by ship, truck, or pipeline—requires significant additional energy inputs for liquefaction, further increasing the costs to export into a global market. Challenges with leakage along the value chain could reduce hydrogen's potential climate benefits, as could the potential regulatory, life cycle, and cost issues with hydrogen storage. Additionally, maintaining hydrogen purity and building out hydrogen infrastructure in the form of pipelines and shipping vessels as well as at ports must also be addressed for a global market to develop. Resolving these transport issues in tandem will require a coordinated effort between companies, national governments, and international institutions, whether through the development of local hub-and-spoke networks or a greater focus on international market development.

Midstream components (i.e., transport and storage) of the hydrogen value chain represent a strong use case for public sector support (MENA workshop). Saudi Arabia's NEOM project, the largest project with an offtake agreement, required significant capital on the supply side—a risk-tolerant offtaker—and government support through infrastructure development. Storage, in particular, will likely play a large role in the European market to stabilize the grid. Using a systems approach could showcase how electrolyzers could become an important "midstream" component of a decarbonized electricity system, as well as highlight the need for an income stream around long-duration hydrogen storage. Using U.S. offshore wind as an example, developers—among a variety of legal and regulatory challenges—also lacked the infrastructure (e.g., substations, AC-DC conversion) on the coastline to connect to the grid. Hydrogen could help store that wind energy, either removing the need for a substation or connecting that energy to demand while substations are under construction.

This perspective is also important when thinking in terms of final energy. Today, electricity represents about 20% of final energy consumption, and as is commonly said, "the rest is molecules" (i.e., fuel). The International Energy Agency (IEA) and International Renewable Energy Agency (IRENA) both estimate that global final energy can at best reach 50% electricity with electrification in a fully decarbonized energy system. Instead of compounding that problem, the industry could focus hydrogen and its derivatives on the energy "storage" required in fuel-based applications that must be decarbonized.

Chapter 4: Global Hydrogen Price and Market Formation

Overall, low-carbon hydrogen demand will need to increase fivefold by 2050 and be met with clean hydrogen production to reach net-zero goals. For this scale to be achieved, the installed production capacity for clean hydrogen will realistically need to increase 75-fold between now and 2030 to build momentum toward midcentury net-zero emissions.[211] If that goal is achieved, hydrogen will still require demand from consumers and industry to be a viable energy source. While it has immense potential, hydrogen also faces numerous challenges, none more so than the price.

The issue lies in the fact that hydrogen, especially green hydrogen, is not currently produced in large amounts. It is expensive to produce by low-carbon or no-carbon technologies. A massive shortfall also remains in the infrastructure needed to transport hydrogen to new demand centers for significant uptake and use. These two issues are compounded by the fact that it will be difficult for a hydrogen market to develop without government intervention and support across myriad areas.

More precisely, historically from the time of the Oil Age of the 1860s and 1870s up to today, the energy production industry at large has always been able to bring a new, more complex, and generally more expensive resource to meet ever-growing energy demand. Each time, through innovation and entrepreneurship, these initially expensive new primary energy resources could be brought within the merit order so that they became affordable for large rollout and consumption. Recent examples of this are deepwater oil development, tar sands, shale oil, and liquefied natural gas (LNG), each a key contributing factor to meeting global demand. And in each of these new layers, especially in the United States, private companies and government played a pivotal role.

Where and how hydrogen markets develop from the present is a point of debate and the subject of many modeling scenarios. However, it is possible to gather insights from the formation of the natural gas markets to better determine the value and risk around green hydrogen and its value chain. Like natural gas, the development of global hydrogen markets, and therefore the price, will eventually depend on the availability and competitiveness of hydrogen compared with other alternative fuels.

The vision for hydrogen is for it to become a globally traded commodity, similar to how oil, coal, and natural gas are traded presently. Economies with excess energy or other resources that can be used to produce hydrogen easily will find export markets in countries that need it as an industrial fuel or energy source.

To get to that point, it is important to understand the evolution of the LNG market in the last 40 years, analyze the lessons the industry learned from this market formation, and develop frameworks that help industries to realize targets in the most efficient and effective ways. It took 20 years for LNG to be traded as a commodity before a first step could be made to liberalize markets and to see the first LNG trades. It then took another 15 years before the United States exported its first LNG from the Lower 48 and advanced the journey toward a fully liberalized global LNG market. Taking these lessons into account, the clean hydrogen market should develop faster so that by 2040 it can achieve a maturity that is comparable with where LNG is today.

Hydrogen Price Formation and Value Chains

Price of Hydrogen

Pricing hydrogen as an energy commodity will be challenging in the early stages of market development (U.S. workshop). Hydrogen pricing mechanisms will need to insulate both producers and consumers from volatility risk and guarantee returns in a nascent but fast-growing market. However, there is still debate as to how hydrogen pricing should occur as its pricing transitions from that of a specialty chemical to a fuel and feedstock.

Reducing risk remains the foremost challenge to facilitating hydrogen consumption. The growth of the LNG industry can be used as a potential proxy, where end-users purchase a specified volume of fuel in long-term contracts (often 20 years). With this in mind, hydrogen price formation should be viewed as scaling up a boutique industry from a specialty chemical to a new, globally traded commodity.

Hydrogen—whatever color—currently is not a commodity. Its pricing is regional and subject to local requirements and expected volumes in industrial usage. Many sources, if not all, are captive. Much of the current production is co-located with demand. In 2023, over 75% of the overall market size in terms of value was the on-site captive production segment, which is estimated to be around $185 billion but projected to be $385 billion by 2030.[212] This has led to the formation of small domestic markets that act regionally. Given that the market is captive, and no commercial trade exists, the costs and final price are generally unknown.

Therefore, prices can vary widely, which is symptomatic of isolated markets. Table 6[213] is an example of hydrogen prices in different regions with natural gas prices taken from major indexes as a reference point, i.e., the rise in natural gas prices may or may not equate to a rise in hydrogen price depending on the locality. As more producers come online and there is increased production and corresponding demand, these markets, while still very limited, will expand and prices will be insulated from large fluctuations.

Table 6. Regional average price comparison of green vs. blue hydrogen ($/kg) with natural gas prices as a reference ($/MMBtu)

January 2024 Costs (these are the average cost-of-production month-to-month costs, including CAPEX)				
Type	**US**	**Europe**[s]	**Asia-Pacific**	**Middle East**[t]
Green[u]	$5.69	$7.00	$4.78	$4.26
Blue	N/A*	$3.37	$2.16	$2.14
Natural Gas[v]	$2.48	$9.48	$11.16	$9.45

s Stand-alone European green hydrogen projects have break-even costs between 6 euros/kg and 14 euros/kg, depending on renewables feedstock—whether offshore wind, onshore wind, or solar—and geographical location (Wood Mackenzie).

t The Middle East contains one from each United Arab Emirates, Saudia Arabia, Qatar, Oman.

u For this table, two types of green hydrogen were available: alkaline electrolyzer and proton exchange membrane (PEM) electrolyzer. We chose to use PEM for this exercise.

v Index for each region: U.S. (Henry Hub), Europe (Netherlands TTF), Asia (LNG Japan/Korea Marker), Middle East Marker (MEM). Natural gas prices were pulled from Jan. 16 and Feb. 16, 2024.

February 2024 Costs				
Type	**US**	**Europe**	**Asia-Pacific**	**Middle East**
Green	$3.21	$5.69	$5.63	$4.26
Blue	N/A**	$2.96	$2.01	$1.96
Natural Gas	$1.68	$7.85	$9.35	$8.38

**The United States has a small amount of blue hydrogen production in the Gulf Coast, but cost estimates were not available. **Grey hydrogen sold for around $1.34/kg in January and $.95 in February.*

Source: EFI table with data from Oilprice.com[214] and Wood Mackenzie, 2024

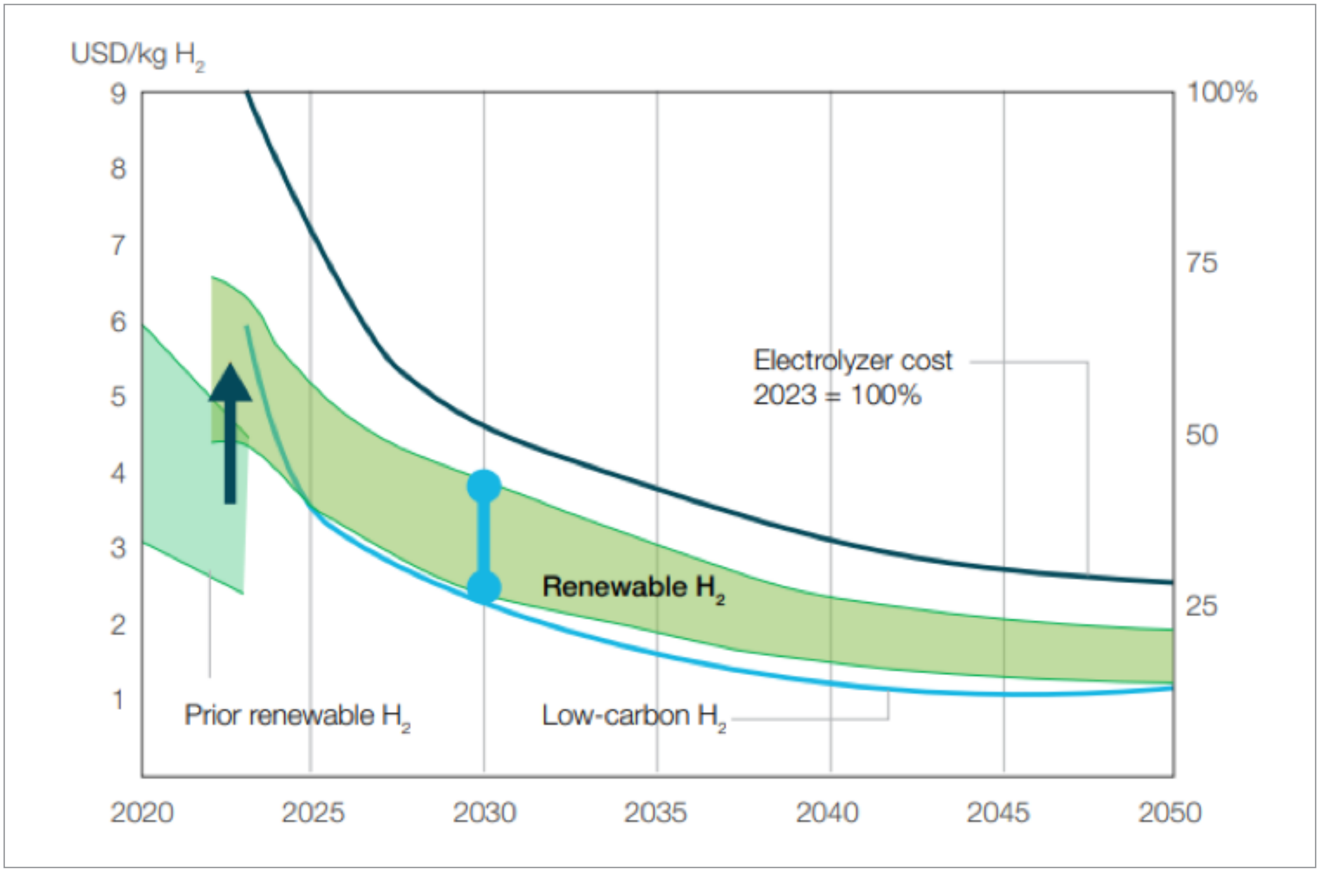
With such disparities in price, transparency in hydrogen cost becomes a vital component of understanding the market development for hydrogen. The levelized costs of energy (LCOE), in this case for hydrogen, are determined by the cost and availability of the energy resources required to produce it, including lifetime costs divided by energy production, net present value of the total costs of construction, and operating lifetime. Cost must also account for a comparison of different technologies, lifespans, projects sizes, and capital costs, among other risks. Understanding the levelized costs of hydrogen helps put these regional markets into a clearer context, although transportation costs can still lead to considerable variation in the final consumer cost (as is the case today for natural gas).

While it is currently cheaper to produce gray hydrogen in the United States, it is more environmentally beneficial to produce green hydrogen—but it is almost four times the cost. This is due to several factors, such as electricity prices, electrolyzer costs, other capital investments, infrastructure, and regulatory influences. In January 2023, the levelized cost of green hydrogen production in the United States ranged between $3/kg and $6/kg, but globally it is higher. The levelized cost of gray hydrogen production outside of the United States typically ranges between $2.8/kg and $3.5/kg based on a gas price ranging from $6 per 1 million British thermal units (MMBtu) to $11 per MMBtu.[215] Prices for green hydrogen are expected to decrease to become market-competitive with blue hydrogen around 2030 in some markets, as Figure 30 shows.[216]

As of December 2023, the Hydrogen Council noted that the estimated levelized cost of producing green hydrogen (LCOH) was about $4.5/kg to $6.5/kg if built today, which is an increase of 30% to 65% compared with the prior year.[217] This increase is due to several factors such as higher labor and material costs, costs for building the balance of electrolyzer plants, a 3 to 5 percentage point increase in capital costs, and an overall increase in renewable power costs of more than 30%.[218]

In Australia, green hydrogen prices could reach parity with blue before 2030. Wood Mackenzie notes that Australia has some of the best renewable resources with accompanying land availability, high wind speeds, and consistent sunshine that allow hybrid onshore wind and solar projects to achieve capacity factors similar to baseload power. This is enabling green hydrogen, powered by hybrid renewables, to deliver a LCOH of $4/kg by around 2027, reaching cost parity with Australian blue hydrogen.[219]

Figure 30. Development of the levelized cost of hydrogen



Source: Hydrogen Council and McKinsey & Company, Global Hydrogen Flows, Hydrogen Council, December 2023, https://hydrogencouncil.com/wp-content/uploads/2023/12/Hydrogen-Insights-Dec-2023-Update.pdf.

HyXchange: Development of a Hydrogen Market Hub in Europe

While there is no set price to trade hydrogen, there are efforts to standardize spot pricing. The HyXchange project is focused on the development of a spot market for hydrogen in the Netherlands. The Netherlands is an interesting market, currently one of the world's largest users of gray hydrogen. It has a large industrial base in the Port of Rotterdam and others in Germany and the Netherlands and has a very proactive policy program to stimulate clean hydrogen development in the coming years. HyXchange runs several variants to this base case, both physical and market variations, to assess the dynamics of the hydrogen spot market. The HyXchange spot market simulation has been subsequently used to develop the HYCLICX spot market indicator. The HYCLICX is an instrument to estimate variable production costs for green hydrogen from electrolysis in the Netherlands. On June 7, 2023, HyXchange published its first issue of the hourly HYCLICX spot market indicator for hydrogen based on the lowest-priced electricity hours during an EU Green Week event in Brussels. In June 2023, the HYCLICX green best 50% euro per megawatt-hour (MWh) High Heating Value marginal cost was 110.02 euros ($119.67), and the HYCLICX green best 50% euro/kg marginal cost was 4.33 euros ($4.71), which resulted in HYCLICX Green best 50% euro/MWh Lower Heat Value marginal cost of 130.05 euros ($141.95).[220]

The HYCLICX price indicator connects the changing costs of hydrogen to the fluctuating hourly rates of the electricity spot market, reflecting the use of electrolysis to produce green hydrogen. By targeting the lowest hourly electricity prices, which typically occur during two periods each day in the Netherlands, hydrogen can be produced most affordably. These periods often align with times of high renewable energy output from wind and solar, which is in line with certification standards and the European Commission's Delegated Act on hydrogen. As a key measure, HYCLICX reports the production cost for hydrogen during the cheapest 50% of electricity hours each month. This method, known as the “50% approach,” is associated with the average time that renewable electricity is readily available. It is important to note that this price indicator focuses on electricity and does not include the following costs:[221]

- Capital costs of investment and financing of electrolyzer
- Upfront project preparation costs
- Fixed administration and overhead costs
- Electricity grid: One-time grid connection fee or cost, if any
- Electricity grid: Capacity-related demand grid tariff (yearly fixed), if any
- Hydrogen grid: All shipper tariffs, connection fees and costs
- Any costs for other means of transportation (by ship or trailer)
- Commercial margin
- Flushing of electrolyzer with nitrogen

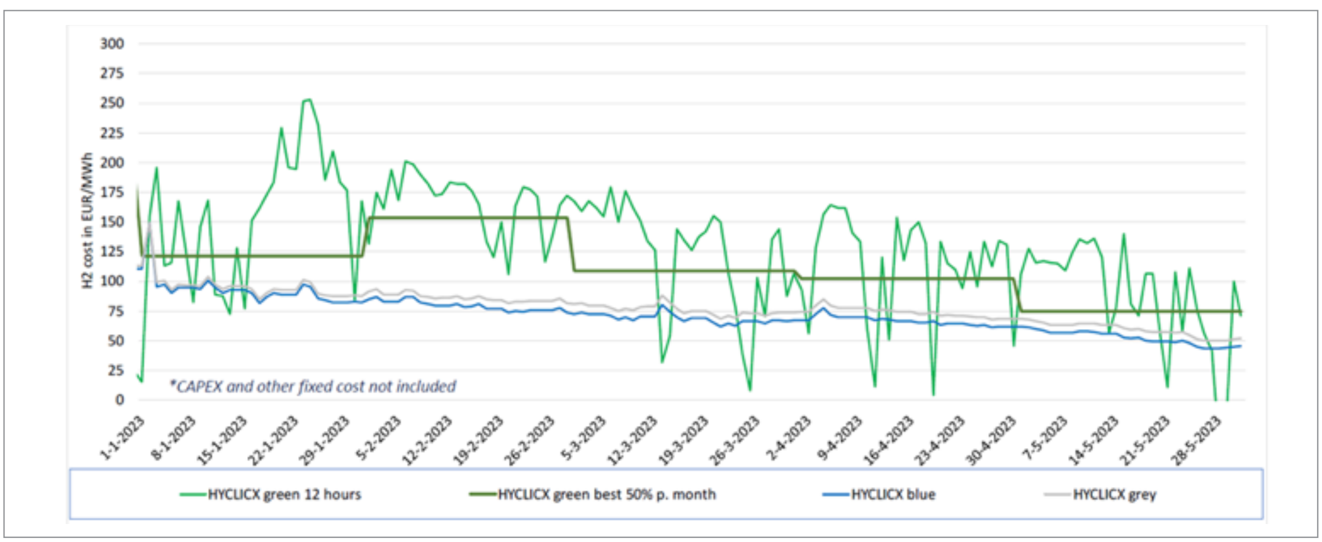
HYCLICX publishes a monthly interval of a selection of relevant indicators for hydrogen:

- HYCLICX green (daily, two six-hour blocks): The cost price for the cheapest (fixed) 12 hours of electricity each day
- HYCLICX green (month): The cost price for the lowest-priced 50% of hours of electricity each month
- HYXCLICX blue (daily): The cost price for blue hydrogen, to allow for comparison
- HYXCLICX grey (daily): The cost price for gray hydrogen, to allow for comparison

The HYCLICX is published monthly, showing in detail the hydrogen production price for the previous months as well as the development dating back one year. The first results[w] are presented in Figure 31.[222]

w For assumptions on this project, please see Annex 1.

Figure 31. HYCLICX pricee inicator



Source: HyXchange, "HYCLICX Renewable Price Indicator." https://hyxchange.nl/hyclicx/#:~:text=The%20renewable%20HYCLICX%20price%20indicator,a%20source%20for%20green%20hydrogen.

As can be seen in Figure 31, the price for green hydrogen fluctuates dramatically but generally remains well above blue and gray hydrogen even when the cheapest 12 hours are singled out.

At present, green hydrogen is broadly uncompetitive, and the commodification of hydrogen has yet to develop. Therefore, adoption will be a function of the industries that have customers who are willing to pay for a renewable power source. Alternatively, there will continue to be a structure of subsidies and taxes to ensure the adoption of hydrogen technologies. The expectations that green hydrogen will come down in price over time, with reasonable learning rates and economies of scale, is probable. However, the limitations of any cost analysis are volume (amount), consistency (specification), and the consequences of an evolving business environment. The commodification of hydrogen has yet to materialize.

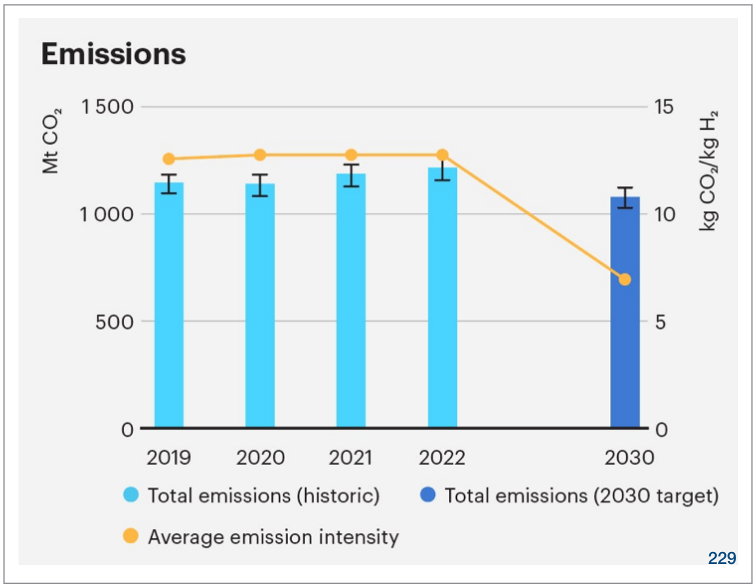
Supply and Demand Dynamics

Clean hydrogen is still in its infancy, and most of the limited global hydrogen supply is produced using fossil sources, such as coal and natural gas, and is mainly associated with the refining and chemicals sectors. Green hydrogen is an even smaller portion of this already limited production. Global hydrogen use grew 3% year on year and hit 95 MMt in 2022[223], but of that, only about 0.8 MMt[224] was green hydrogen.

- About 0.86 MMt per annum (MMtpa) of green hydrogen supply is operational today:[225]
- Low-carbon hydrogen accounts for about 860 kilotons per annum (Ktpa), which is about 1% of the gray hydrogen market today.
- North America is the largest market in terms of committed clean hydrogen capacity with volumes of about 1.8 MMtpa. About two-thirds of this capacity is in the United States and one-third in Canada. Around 90% of these volumes are low-carbon hydrogen (blue hydrogen), potentially due to higher maturity and driven by the early deployment of carbon capture and storage (CCS) technology in gray hydrogen production.

In 2022, Australia led in total new low-carbon hydrogen project announcements.[226] The following year, the global hydrogen project pipeline consisted of 89 MMtpa, and a Wood Mackenzie analysis found that the United States surpassed Australia in terms of total projects planned. However, Australia still has one of the largest hydrogen project pipelines, with 12 MMtpa of new hydrogen production planned, of which 96% is for green hydrogen.[227] The IEA notes that hydrogen "remains concentrated in industry and refining, with less than 0.1% coming from new applications in heavy industry, transport, or power generation. Low-emissions hydrogen, as seen in Figure 32, is being taken up very slowly in existing applications, accounting for just 0.7% of total hydrogen demand, implying that hydrogen production and use in 2022 was linked to more than 900 MMt of CO_2 emissions."[228] This amount equates to the total CO_2 emissions of Canada and Australia combined.

Figure 32. Emissions produced from hydrogen



Source: IEA, Hydrogen—Breakthrough Agenda Report 2023—analysis, 2023, https://www.iea.org/reports/breakthrough-agenda-report-2023/hydrogen.

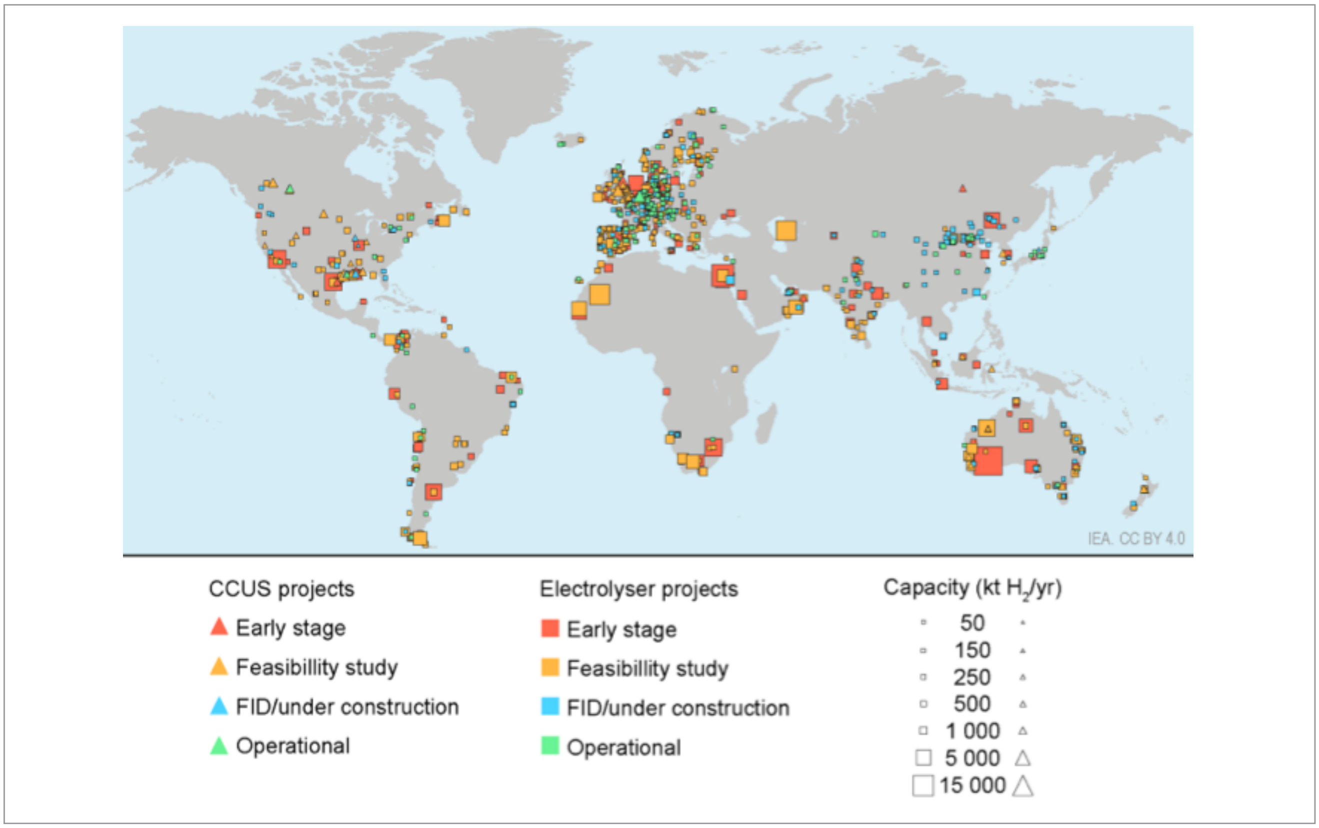
However, on a global scale, hydrogen momentum is growing, with numerous projects across the hydrogen spectrum being announced, marking the early stages of design and planning. Globally, the industry has announced 1,418 project proposals, of which 1,011 plan full or partial deployment by 2030. Since October 2023, Europe has announced 193, followed by Latin America, Oceania, and North America with 85, 75, and 68, respectively.[230] The 1,418 projects represent 45 MMtpa of clean hydrogen supply announced by 2030, 70% of which is renewable and 30% is low-carbon.[231] Figure 33 shows different regions and the different types of projects.

Additionally, Bloomberg notes that green hydrogen projects are being built at a rapid rate as equipment suppliers were expected to ship 1.7 GW to 2.1 GW of electrolyzers in 2023, twice as much as in 2022.[232] One sign that green hydrogen will continue to procure more market share is that blue hydrogen projects are taking longer to develop because of their larger size and technological complexity.[233]

Yet, few green hydrogen projects of significant size have progressed to the construction stage. Shell's 200 MW electrolyzer project[x] in Rotterdam is a rare example of construction in Europe. This early phase is reminiscent of the formative years of the renewable energy sector and the oil industry, where it took years from the initial business development to the realization of substantial investment decisions and operational projects. Additionally, like the renewable energy industry, few projects have reached a final investment decision (FID), leading to uncertainty about which technologies and applications would succeed long term.[234]

x The 200 MW electrolyzer will be constructed on the Tweede Maasvlakte in the Port of Rotterdam and will produce up to 60,000 kilograms of clean hydrogen per day.

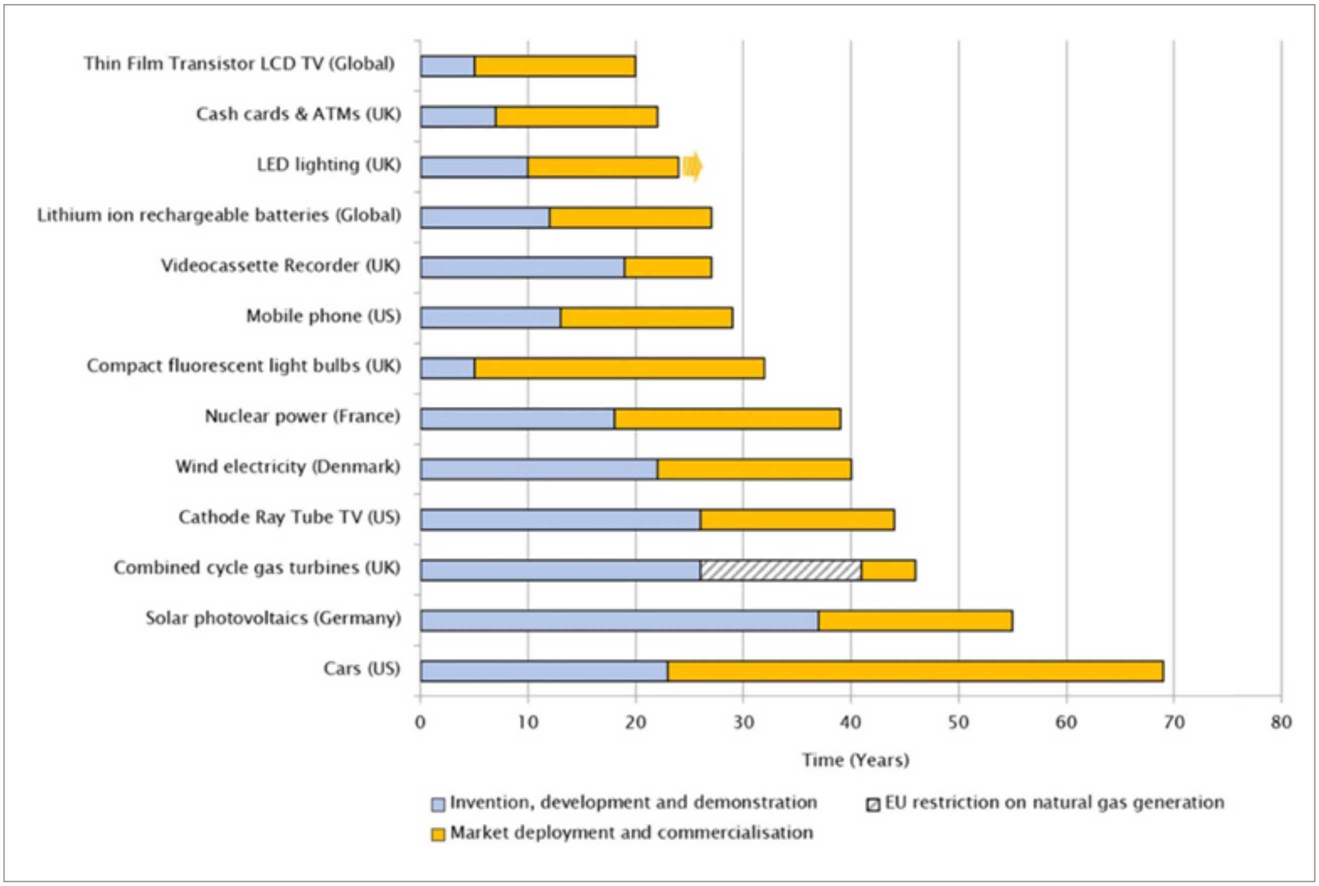
Figure 33. Map of announced low-emissions production projects



Source: IEA, Hydrogen—Breakthrough Agenda Report 2023—analysis, 2023, https://www.iea.org/reports/breakthrough-agenda-report-2023/hydrogen.

One aspect that needs to be considered with any new decarbonization technology is the timeline from innovation to commercialization. These timelines can span anywhere from 20 to 60-plus years. Figure 34[235] shows ubiquitous technologies, such as wind and solar, which took decades to reach commercialization. When considering decarbonization strategies and technological advancements in hard-to-abate sectors, these aspirations and realistic timelines of research and development need to be compared against net-zero goals for the most effective utilization and investment of capital. This is precisely why governmental support in this early stage of technology development and deployment is crucial. The whole purpose of current policies, whether regulatory or financial, and whether supply-side or demand-side focused, is to accelerate the pace of commercialization. Otherwise, we will be looking at the same sort of timeline for hydrogen as for the other new technologies and products shown below.

Figure 34. Energy technology development: From innovation to commercialization



Source: Robert Gross et al., "How Long Does Innovation and Commercialisation in the Energy Sectors Take? Historical Case Studies of the Timescale from Invention to Widespread Commercialisation in Energy Supply and End Use Technology," Energy Policy 123 (2018): 682-699.

Market Structures and Value Chains

The green hydrogen ecosystem is diverse, involving myriad actors across various developmental value chains. This includes renewable power producers, utilities, oil and gas companies, midstream power and pipeline companies, storage entities, and new entrants focusing on green hydrogen production. These entities are supported by original equipment manufacturers and contractors, both established industrial entities and new pure-play companies.

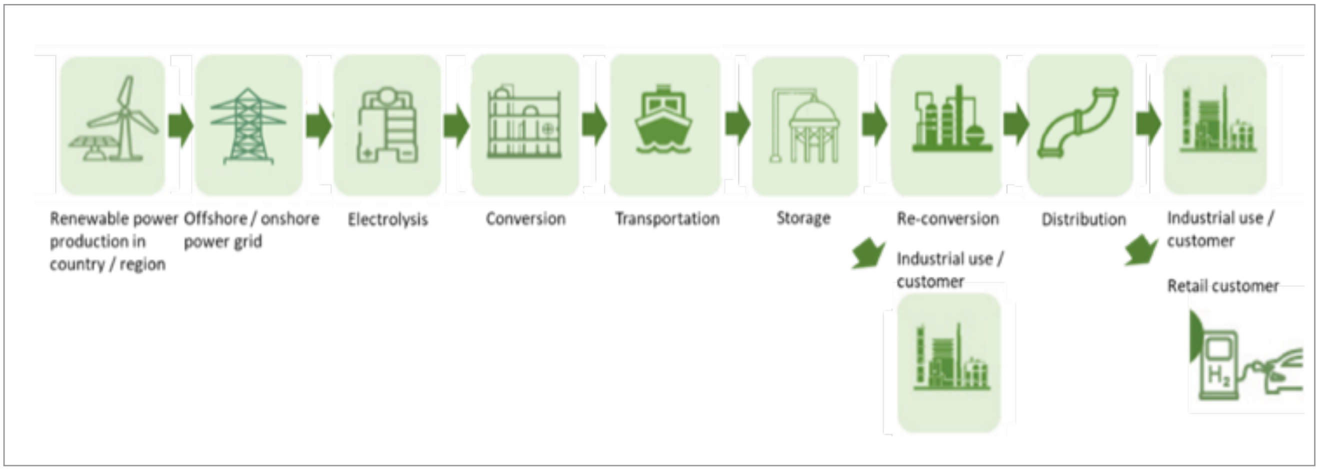
The complexity of green hydrogen lies in its intricate and segmented value chains, the diversity of hydrogen carriers in gaseous and liquid forms, and a competitive landscape that includes many actors. These range from integrated oil and gas companies to independent storage providers, industrial gas producers, chemical and fertilizer manufacturers, heavy industry, renewable electricity firms, and utility companies. Each competes for a portion of the value chain, contingent on their financial capabilities and the management of complex investments and contractual relationships over extended periods and distances.[236] These value chains, as seen in Figure 35, can be categorized into domestic-based and export-import-based green hydrogen chains. Each has distinct cost profiles, levels of corporate and government involvement, interdependencies, customer bases, and risk profiles.

The global hydrogen value chain retains most of the components of the domestic value chain but also requires deep-sea vessels for the seaborne transport of converted hydrogen. Europe's drive for overseas green hydrogen production stems from its need to decarbonize industries and transport sectors faster than it can produce hydrogen domestically. However, many selected producer countries lack experience in developing large-scale renewable (wind or solar) to hydrogen projects. They might not have the necessary infrastructure, credit ratings, or professional expertise. Only established oil and gas companies today have the experience to manage such full value chain projects.

Major oil and gas companies are reconsidering their renewable energy strategies, which might slow down the development of export-import projects. Storage companies face decisions on converting terminals for hydrogen, green methanol, ammonia, or liquid organic hydrogen carriers. Shipping companies will need to decide on converting LNG carriers or building new hydrogen-dedicated ships. Exporting countries must choose which market to serve and what type of green hydrogen carrier to produce.

Traditional oil and gas producers are well positioned to be hydrogen producers (U.S. workshop). Stakeholders in the hydrogen industry

Figure 35. Global export-import hydrogen (carrier) value chain



Source: Jan-Hein Jesse, attached EFI white paper, Hydrogen Market and Price Formation: A European Perspective.

largely agree that the world's largest fossil fuel-producing nations can lead the decarbonization of the industrial sector, particularly using clean hydrogen in the ammonia, refining, and methanol sectors. Successfully implementing these projects at the local and regional levels is essential to de-risk investment. At the same time, these traditional energy producers have acknowledged the need for incentives and taxation to actually spur activity around broader hydrogen market development. One potential mechanism to encourage this market development would be to rely on these nations' sovereign wealth funds, which could direct funding toward hydrogen development. Such policies specifically geared toward technological improvements and reduced production costs could support these oil- and gas-producing nations to transition their existing hydrogen use while also encouraging hydrogen use in new demand applications (e.g., power and energy storage, steelmaking, cement production, heavy-duty transportation).

Some companies may prefer to control the entire value chain by creating integrated hydrogen hubs like the ones in the United States. Contradictorily, the United States' segmented value chains for natural gas allow additional flexibility, giving an insight into how the hydrogen market could develop domestically. However, in Europe, competition laws and the uncertainty of winning wind energy bids can delay downstream development, increase costs, and lead to a cautious approach from potential customers. The law firm Skadden notes that because the green hydrogen industry and technology are still emerging, developers and financiers will need to consider additional project risks relative to projects with existing mature technology.[237] The overarching question is the feasibility and speed at which large international energy clusters can develop, especially when governments dictate the terms for commercial participation and investment decisions.

The financial industry will require high-yield investments that demonstrate value across the supply chain (U.S. workshop). Stakeholders across the hydrogen value chain have indicated that long-term offtake agreements are necessary for any real financing to occur at the scale required for regional and global hydrogen market development, especially to demonstrate demand and showcase public-private partnerships. There is also potential for equity markets or venture capital to be used as financing mechanisms that could help near-term hydrogen projects get off the ground. Another option would be to create a government backstop, whether through sovereign guarantees or blended financing, to provide more investment certainty as the hydrogen market scales up.

While project financing is necessary, developers need to attract equity investments. This equity investment gap is apparent when comparing hydrogen financing, particularly around electrolyzers, with how renewable energy financing has occurred over the past two decades. In particular, renewable energy financing has generally come from small startups' venture capital investments, whereas electrolyzer production to date is largely confined to large multinational companies.

Hydrogen Price Formation in the Future: Factors Affecting Hydrogen Cost of Supply

While clean hydrogen is a realistic and plausible pathway for significant decarbonization, the energy source faces immense difficulties in becoming market-viable on its own. This includes financial barriers, long project financing timelines, and infrastructure development. While taking different forms in different regions, government intervention supports this process of hydrogen becoming market-viable, but different countries are using unique pathways to accomplish this.

Advocacy and buy-in are necessary for the development of a hydrogen market (U.S. workshop). Stakeholders have emphasized that hydrogen is still misunderstood in its role as both a feedstock and a fuel, which could impact development opportunities. To improve knowledge sharing, developers could exchange early hydrogen success stories to increase community awareness as well as facilitate hydrogen's use as a fuel.

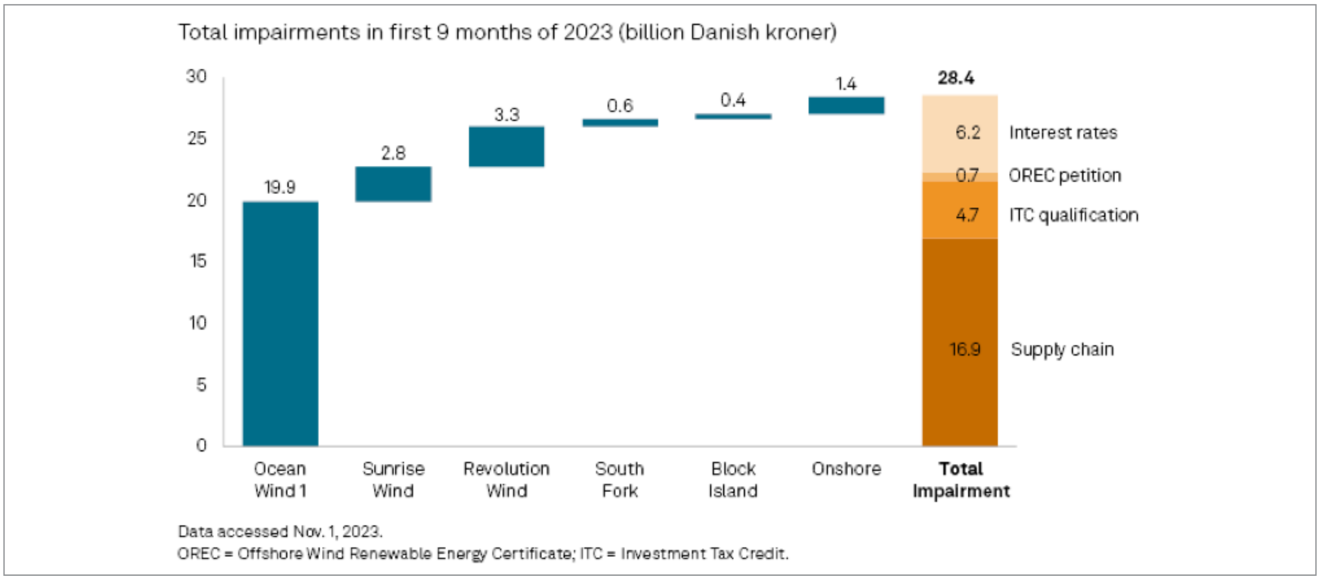
Financial Barriers

As green hydrogen gains more market share and production increases, it will continue to face physical and financial challenges that will impact price formation over the next five to 15 years. Lack of access to capital is only part of the problem for the growth of the green hydrogen industry. While more than a thousand projects have been announced, only a fraction have reached FID. Many projects are in various stages of development, but very few have been able to reach FID and move into the execution phase. During the time that the first projects were prepared for FID and execution, the costs of capital and materials have changed substantially compared with the start of these projects.

The price of clean hydrogen will be determined by the capital expenditure (CAPEX) costs, the electricity price for green hydrogen, and the natural gas price and CCUS cost for blue hydrogen. Between 70% and 80% of green hydrogen production costs are for electricity, which is leading green hydrogen developers to concentrate on projects in regions with both large amounts of renewable energy and access to water for electrolysis, such as Australia and the Middle East.[238] In general, the MENA region has the capability to implement large-scale desalinization projects.

There was a broad consensus that electrolyzer CAPEX costs would come down rapidly, even faster than the solar and wind industries experienced over the previous decade. However, that has not been the case as of late. CAPEX costs are rising not only for the first hydrogen projects but also for wind, especially for offshore wind, a core supplier of power to produce green hydrogen. These costs are causing numerous developers to be unable to economically supply power at the rates previously agreed to. For example, Denmark's Ørsted, one of the world's largest wind developers, took a $4 billion charge in November 2023 for pulling out of two projects off the coast of New Jersey (Figure 36).[239] The company's value is 75% less than in early 2021.[240] As a whole, renewable and low-carbon hydrogen investment costs have risen 40% over the past two years, and higher electricity prices have prompted fossil fuel competitiveness to rise.[241]

Figure 36. Ørsted writes down U.S. offshore wind portfolio

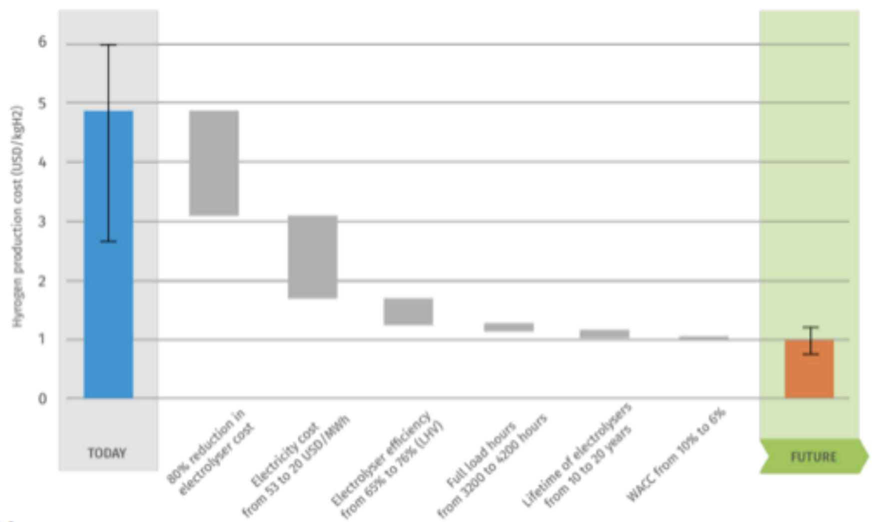


Source: S&P Global Commodity Insights, "Ørsted surprises with US offshore write-down scale as analysts welcome clarity", 2023, https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/216-rsted-surprises-with-us-offshore-write-down-scale-as-analysts-welcome-clarity-78194923.

Inflation is also affecting the renewable energy sector in Europe. The industry is facing a significant increase in the LCOE because of rising equipment, labor, and financing costs. For example. offshore wind LCOE, which was expected to decrease, had instead risen from 62 euros/MWh ($67.26) in 2019 to 80 euros/MWh ($87.02) in 2024 and is projected to reach 90 euros/MWh ($97.90) by 2030. This increase is attributed to a 25% to 35% hike in equipment costs and a doubling in financing expenses since 2021. The complex and lengthy permitting processes, which involve multiple government levels and are subject to political influence and environmental litigation, add to the uncertainty and costs. These challenges have led to stranded energy projects and demands for higher upfront payments, impacting profitability and the willingness of companies to commit to FID in a rising-cost environment.

Developers view improvements in electrolyzer technologies as a major cost reduction driver (MENA workshop). Driving down the costs of production would contribute to a greater willingness among off-takers to commit to long-term contracts. Still, there is a need for increased clarity around regulations and subsidies—especially within niche markets like green steel, sustainable aviation fuel (SAF), and shipping with hydrogen derivatives (e.g., ammonia, methanol)—for these industries to commit to hydrogen. Cost forecasts are shown in Figure 37.

Figure 37. Hydrogen cost forecasts



Source: IRENA, 2020a

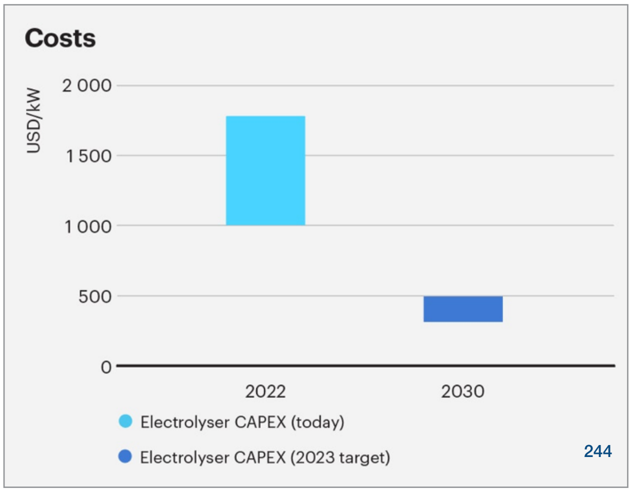
Note: "Today" captures best and average conditions. "Average" signifies an investment of USD 770/kilowatt (kW), efficiency of 65% (lower heating value -LHV), an electricity price of USD 53/MWh, full load hours of 3200 (onshore wind), and a weighted average cost of capital (WACC) of 10% (relatively high risk). "Best" signifies investment of USD 130/kW, efficiency of 76% (LHV), electricity price of USD 20/MWh, full load hours of 4200 (onshore wind), and a WACC of 6% (similar to renewable electricity today).

Based on IRENA analysis

Source: International Renewable Energy Agency, "Renewable Capacity Statistics 2020," https://www.irena.org/publications/2020/Mar/Renewable-Capacity-Statistics-2020.

The industry's capital-intensive nature, with high CAPEX requirements for offshore wind and electrolyzer projects, poses a challenge. The European Union's target for renewable energy sources capacity by 2030 necessitates substantial investment, with estimates suggesting a need for more than 400 systems like Shell's 200 MW electrolyzer project in Rotterdam.[242] However, as the production of electrolyzers grows in scale and becomes more efficient, it is estimated that the CAPEX could fall by between 35% and 65% in the next decade, making green hydrogen at a cost under $2/kg achievable in most markets by 2040 (Figure 38).[243]

Figure 38. Electrolyzer CAPEX costs in 2023 vs. projected



Source: IEA, Hydrogen – Breakthrough Agenda Report 2023 – analysis, 2023, accessed February 6, 2024, p. 57, https://www.iea.org/reports/breakthrough-agenda-report-2023/hydrogen.

The CAPEX costs are substantial: In Europe, it is estimated that a 1 GW offshore wind park to supply renewable electricity for green hydrogen costs $3 billion. A 1 GW green hydrogen project with electrolyzers currently costs between $2 billion and $3 billion, or more, based on the estimated cost of Shell's project, when all outside battery limit costs are included.

The concentration of critical minerals and electrolyzer manufacturing represents a challenge to widespread emergence of a green hydrogen economy (U.S. workshop).

In the Netherlands, the commercial building blocks of a domestic hydrogen value chain will require CAPEX investment between $5 billion and $6 billion for a 1 GW system, which is a conservative estimate. Additionally, the offshore and onshore power cables and the costs to convert natural gas pipelines into hydrogen pipelines, to be executed by the state-owned energy companies, inflate the overall costs. Finally, there are increased technology and delivery risks, which create uncertainty around when these companies will take FID and thus around future production volumes and the performance of green hydrogen and its derivatives.

The concentration of critical minerals and electrolyzer manufacturing represents a challenge to widespread emergence of a green hydrogen economy (U.S. workshop). Today, many developers have expressed concern over the control of electrolyzer and photovoltaic (PV) panel construction, which is largely centralized in China to date. The two most prominent types of electrolyzers—alkaline and proton exchange membrane (PEM)—have varied mineral requirements, and the rise of hydrogen demand could subsequently create greater competition for nickel, platinum, and other minerals essential to the production of electrolyzers and fuel cells.[245] Solid oxide electrolyzers have fewer mineral requirements but are further from market readiness. Ultimately, secure access to metals and minerals for electrolyzer and fuel cell production will determine hydrogen costs and how soon these technologies can be used at the scale necessary for decarbonizing hard-to-abate sectors.

Buildout of green hydrogen relies on critical minerals like titanium, nickel, platinum, and zirconium. These are key components of electrolyzers that facilitate the conversion of electricity and water into hydrogen. The price and availability of these materials will be a key driver for the buildout of hydrogen production capacity. The issue is that the world faces a rapidly increasing demand for these resources that are produced from many different technologies. Many of the same minerals needed for electrolyzers are components of solar cells, transistors, and wind turbines. In short, the rapid pace of technological growth in the energy and technology sectors now necessitates an increase in the production of these critical minerals. The mining industry is known for its high energy consumption and greenhouse gas (GHG) emissions, contributing to its reputation as an environmentally detrimental sector.[246]

Mining operations for these minerals also demand substantial water resources, which could lead to water contamination and scarcity issues. Such activities are particularly concerning in regions where water is already scarce, like Chile's Atacama Desert, a crucial site for copper extraction. The process of extracting and processing these minerals, including ore transportation and dust suppression, necessitates considerable water usage. Moreover, mining activities generate vast amounts of waste, often stored in tailing ponds, which, when they fail, release toxins into nearby water systems. In the U.S., copper mining alone contributes to a significant portion of metal mining and processing waste, indicating the scale of the problem.[247]

The energy costs associated with mining these minerals are also significant, although exact figures can be elusive because of varying technologies and geographical factors. The extraction process requires energy, and the subsequent processing and transportation stages further add to the energy cost.

Furthermore, the environmental degradation resulting from mining operations is considerable. Besides water issues, mining contributes to air pollution, deforestation, and biodiversity loss, often in protected areas. Nearby communities bear the brunt of these activities, raising health and enduring land-use and environmental justice conflicts.[248]

The cost of facilities for mining these critical minerals can be high, although specific figures may vary based on the region and the technology employed. The financial investments cover exploration, extraction, processing, and waste management infrastructures, among other costs.[249]

Efforts are underway to mitigate the environmental and social impacts of mining operations. These include implementing better regulations, lower-impact mining methods, improved community consultations, comprehensive mine closure and rehabilitation procedures, and innovative waste reduction or reuse strategies. Some mining companies are also investing in technologies like desalination to reduce their reliance on local freshwater supplies.[250]

Final Investment Decisions

Projects are reaching fruition, but at a much slower pace than reports based on aspirational announcements would suggest. CAPEX is just one of the financial barriers impeding hydrogen from becoming market viable. Procuring the investments and having FIDs confirmed is vital for the long-term success of the industry and the energy source. The Hydrogen Council notes that for developers to take an FID, they want secured offtake and, potentially, government subsidies.[251] Currently, most projects at or past FID include either captive offtake (developed by companies with internal demand for hydrogen) or long-term offtake contracts.[252] Without the investment available, the industry could lose momentum. Stakeholders, however, must realize that some country-specific goals may not be feasible within the periods proposed.

For example, the Dutch government's goal in the Paris Agreement is to have 4 GW of hydrogen factories by 2030 and 8 GW by 2032. The 4 GW is equal to 20 hydrogen factories the size of the singular Shell plant under construction in Rotterdam. Therefore, FID would have to be made very soon for these to be built and operational by 2030.

Despite this, momentum is building, with North America now accounting for 2.4 Mt p.a. of clean hydrogen capacity past FID, primarily largely thanks to the 45Q tax credit for carbon capture and storage (CCS). As a result, North America now represents nearly 90% of the world’s low-carbon hydrogen capacity that has passed FID, demonstrating significant progress over the past year.[253]

The Hydrogen Council estimates that more than 1,572 renewable and low-carbon hydrogen projects, requiring $680 billion of investment by the end of 2030, have been announced globally. Of the 1,572 hydrogen projects, 434 of them have reached FID, an 18% increase over last year’s figures. The projects that are reaching FID, however, may not be representative of the future of the industry as most of these are smaller projects integrated with offtakes funded by oil and gas or ammonia companies that are already producing hydrogen.[254] The projects that are reaching FID are also not representative of the future of the industry as most of these are smaller projects integrated with offtakes funded by oil and gas or ammonia companies that are already producing hydrogen.[255] Additionally, even though investments are increasing, these remain scattered and uncoordinated across multiple end-use sectors, specifically refining, transportation, and ammonia for fertilizer production.[256]

The expected learning curve from accelerated growth in new green hydrogen projects is highly anticipated. In addition, cost inflation on CAPEX and operational expenditures is high and poised to persist for a while, potentially becoming an acute issue once accelerated growth starts to kick off. Firsthand experience from the oil and gas industry’s investment phase between 2000 and 2008-9 and after the great financial crisis (notably in Australian LNG) can explain what could happen in the global renewable energy sources and green hydrogen market in the coming years if policymakers drive investments to triple in this space to achieve their ambitious climate change targets.

Box 6. Comparison of operation capacity by region where clean hydrogen has reached FID

As of 2024, approximately 4.6 MMtpa of clean hydrogen has passed FID, in addition to the 895 Ktpa operational capacity. Of the 4.6 MMtpa, about 2.4 MMtpa is renewable hydrogen and the remaining 2.2 MMtpa is low-carbon. Most of the low-carbon hydrogen volumes at or past FID are still concentrated in North America, while renewable hydrogen is more geographically dispersed: China remains the largest market, producing over 55% of committed renewable volumes, followed by North America and the Middle East. Europe, despite having the largest announced investments with 13 MMtpa announced by 2030, has the smallest committed supply capacity at 0.3 MMtpa, tied with the Middle East. This may be driven by a lack of transparency on regulatory frameworks, subsidies, and high energy prices following the start of the 2022 war in Ukraine.[257]

Moreover, Europe’s industry is struggling to cope with higher costs, lower demand, higher energy prices, and growing regulatory and political uncertainties. This raises the question of whether hydrogen could stay competitive in the current landscape or whether other locations for future growth outside the EU provide better alternative futures.

Infrastructure Development

Infrastructure deployment for green hydrogen is gaining momentum, which is crucial to ensuring consistent supply and demand while keeping the cost of green hydrogen low. The IEA notes that "infrastructure is needed not only to connect regions where low-emission hydrogen can be produced at low cost with centers of demand and to manage fluctuations in production and demand but also to ensure the resilience of the system in the event of supply disruptions."[258] However, the lack of infrastructure and the estimated construction timelines for these projects are not advantageous for the hydrogen industry. The few existing green hydrogen projects are small-scale and piecemeal, representing less than 1% of total hydrogen production over the past three years. This makes the cost of infrastructure—which becomes tolerable when there is a bigger demand—high on a per-unit basis.[259]

Dedicated distribution and transportation infrastructure for hydrogen exists but is limited in size, and the reach of the industry is in the early stages of development. Energy infrastructure development generally has long lead times, averaging between six and 12 years for natural gas pipelines, port terminals, and underground gas storage facilities. Gas infrastructure developments are large civil engineering projects, often spanning several jurisdictions, which can lead to delays due to permitting issues and a lack of sociopolitical support. It is, therefore, critical to start infrastructure planning well in advance, even before production and demand are fully established.

Figure 39. Current hydrogen pipelines in the United States

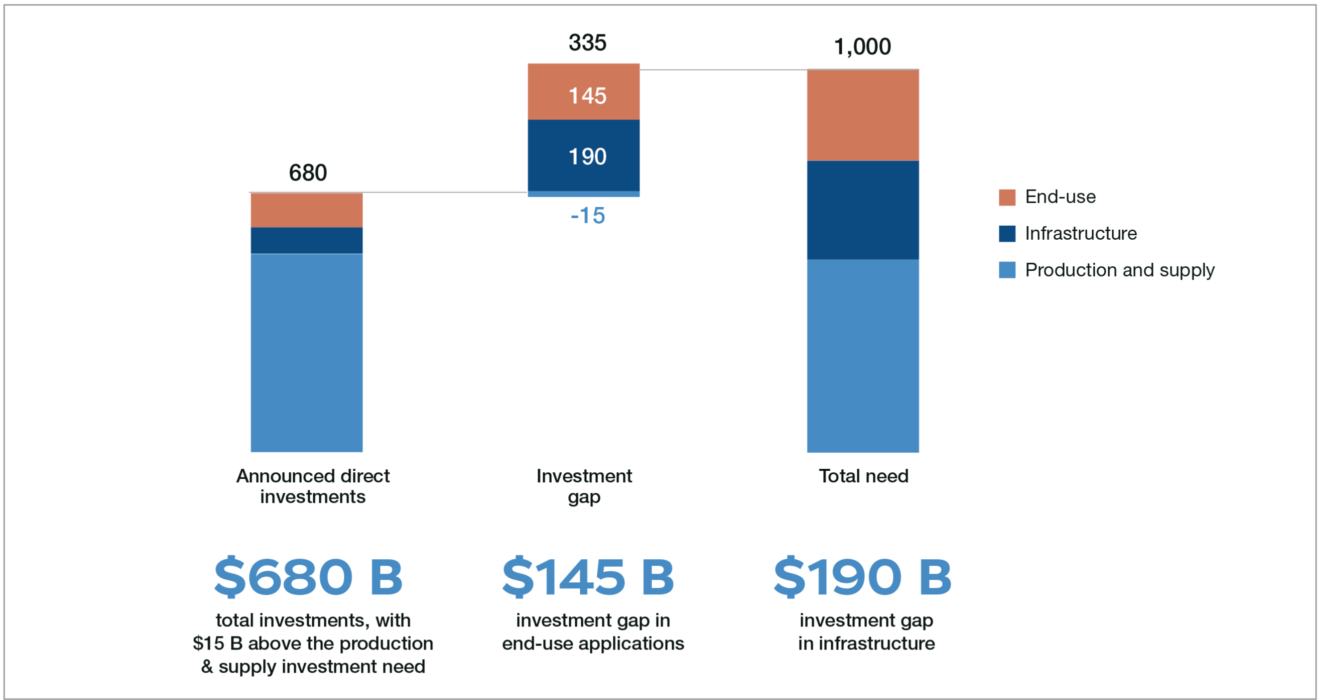
Data from: U.S. Department of Transportation. "National Pipeline Mapping System Map Tool." https://data.transportation.gov/Pipelines-and-Hazmat/National-Pipeline-Mapping-System-Map-Tool/uhry-zmej/about_data.

If natural gas consumption declines, repurposing existing natural gas infrastructure for hydrogen, when technically feasible and safe, could mitigate the risk of possible stranded assets. This could reduce the environmental impact associated with manufacturing and laying new pipelines, thereby lowering investment costs and potentially reducing lead times. However, this is mostly applicable in Europe, as the United States' gas network generally consists of older pipelines that would need to be replaced instead of retrofitted as they could not carry hydrogen. Around 3,100 miles of hydrogen pipelines are in operation worldwide, mainly in the United States and Europe (Figure 39). These pipelines are relatively small, with diameters of less than 18 inches, connecting refineries and chemical complexes, operating under static loads, and all onshore. Currently, there are approximately 6,200 miles of proposed hydrogen pipelines[y], around 80% of which are in Europe, and some are under construction.[260]

Yet, there is still a significant gap in the infrastructure proposed and the infrastructure needed for a truly operational hydrogen market. This is especially true for low-carbon hydrogen projects that face challenges such as large-scale infrastructure for carbon capture, transportation, and storage, which must be built, requiring permitting and significant capital and labor.[261] Committed investments in hydrogen infrastructure have grown from about $5 billion to about $7 billion, of which more than three-quarters are in Asia.[262] However, as seen in Figure 40[263] there is still a significant gap between the announced hydrogen investments and the required capital needed by 2030 to reach climate benchmarks.

y This is 1% of the total length of global natural gas transmission pipelines.

Figure 40. Announced and required direct investments into global hydrogen until 2030, in billions of dollars



Source: Hydrogen Council and McKinsey & Company, Hydrogen Insights 2024, September 2024, p. 15, https://hydrogencouncil.com/wp-content/uploads/2024/09/Hydrogen-Insights-2024.pdf.

The Center for Strategic and International Studies notes that the limited availability of hydrogen infrastructure will constrain scaling in cases where co-location is not feasible.[264] However, as production costs decrease, hydrogen distribution and associated delivery costs will likely be a larger portion of the final costs, making the cost-effective development of related infrastructure essential for the U.S. hydrogen economy to become vibrant and sustainable.[265] At the same time, this will be an internal development for countries (except for intra-European Union projects). The transport of hydrogen will eventually grow from local to regional to international.

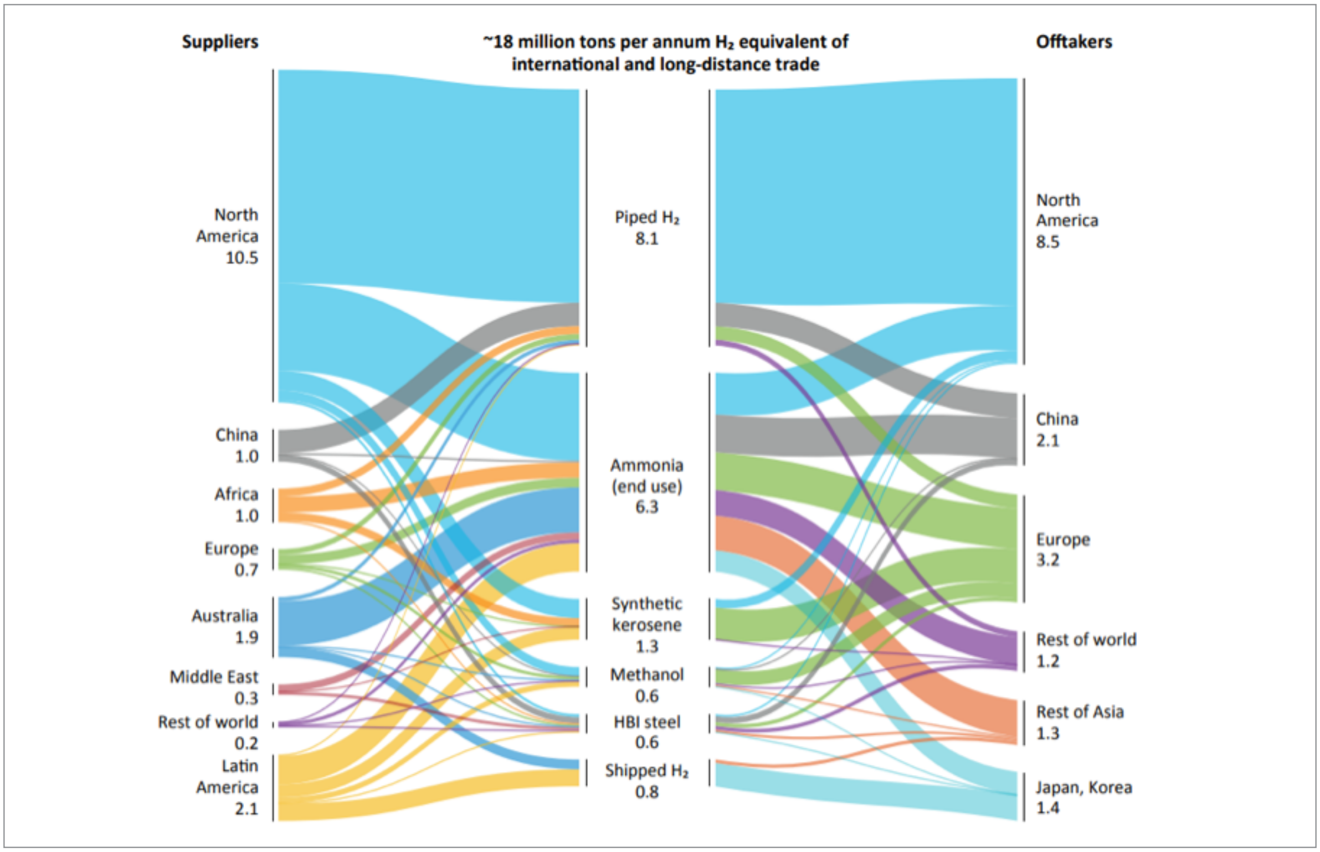
Hydrogen in Transportation and Shipping

For hydrogen to be a market-viable commodity, it must be able to be traded in a market context, and to do that, it needs to be transported and stored appropriately and cost-effectively. This poses a challenge as, currently, pure hydrogen is difficult to transport and store; like natural gas, hydrogen needs to be compressed or liquefied because, at normal temperatures, it takes up significant space and is not feasible to transport.[266]

To transport hydrogen over long distances where pipeline transmission is not feasible or in regions without suitable geological conditions for underground storage, hydrogen needs to be converted into denser forms. Among such alternatives, liquefied hydrogen, or carriers such as ammonia and liquid organic hydrogen carriers are promising options. However, while the conversion of hydrogen to ammonia for use as ammonia is already well established, conversion back to hydrogen is not yet available on a commercial scale.

Transportation is a major factor in hydrogen's costs. Figure 41 incorporates these costs in long-distance flow forecasts. For some countries, an

Figure 41. 2030 global clean hydrogen long-distance flows



Source: Hydrogen Council and McKinsey & Company, Global Hydrogen Flows, December 2023, https://hydrogencouncil.com/wp-content/uploads/2023/12/Hydrogen-Insights-Dec-2023-Update.pdf.

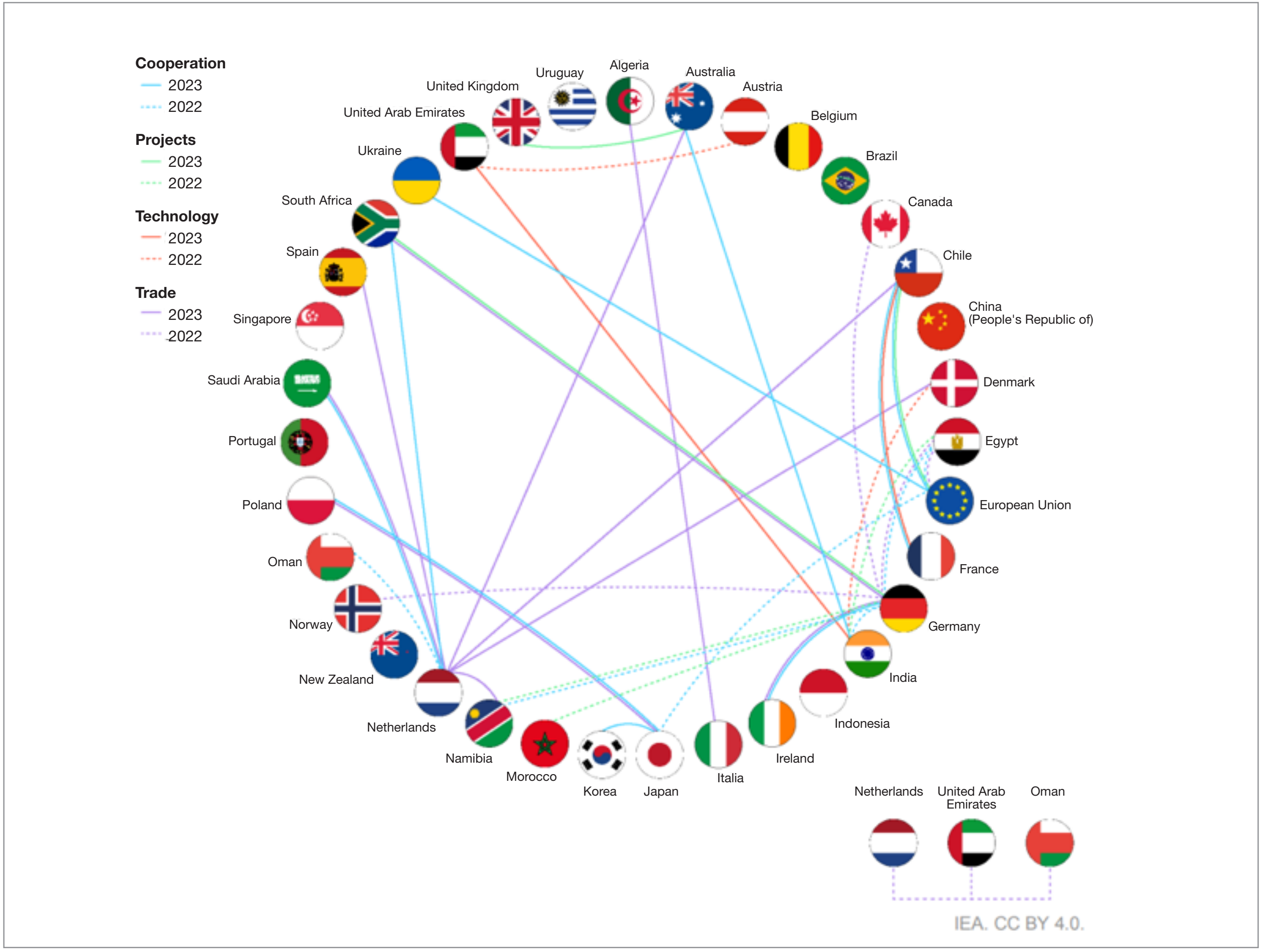
indigenous supply solves this issue. As smaller national domestic markets form they will eventually transition to a larger, more regionally interconnected markets that could, in theory, develop in a similar manner to the major natural gas market formations seen over the past 10 to 15 years. Countries like Australia, which is geographically isolated, could be world pioneers in shipping hydrogen, as the first shipment of liquefied hydrogen went from Australia to Japan in February 2022.[267]

Wood Mackenzie notes that Australian hybrid projects should be able to deliver some of the most competitive LCOH in the market, enabling the country to position itself as a major exporter of low-carbon hydrogen.[268] Australia is expected to export nearly 1 MMtpa or 50% of its low-carbon hydrogen supply by 2030. With only two major import markets (EU and Northeast Asia) and 14 exporter countries, Australia will face significant competition to secure offtake agreements in the hydrogen market.[269]

Bilateral Agreements

Numerous countries have started to sign bilateral agreements (Figure 42) to secure hydrogen both as a means of enhancing energy security and as support for reaching decarbonization goals. Additionally, outside of climate and energy goals,

Figure 42. Co-operation agreements between governments on hydrogen since August 2022



Source: International Energy Agency, Global Hydrogen Review 2023, https://www.iea.org/reports/global-hydrogen-review-2023.

these agreements can stimulate market formation through more robust trade relationships and developing market mechanisms such as joint ventures. Additionally, technology transfer is important as hydrogen's technological development is still in its infancy. These bilateral agreements can allow countries to benefit from each other through technology sharing and support of investments in hydrogen demand and supply infrastructure.

Clean Hydrogen Collaboration Between Australia and Japan

In February 2022, Australia and Japan established an AU$150 million ($101 million) Australian Clean Hydrogen Trade Program. The program will support Australian-based hydrogen supply chain projects that secure overseas investment and will focus on the export of clean hydrogen to Japan under the Japan-Australia Partnership on Decarbonization through Technology.[270]

The program aims to assist in accelerating the development of an Australian hydrogen export industry to become a supplier of choice for Japan and the region.[271] Australia's Department of Foreign Affairs and Trade notes that in 2020, Japan was Australia's second-largest export market and largest source of new foreign direct investment.

Japan and Saudi Arabia's Lighthouse Initiative

In July 2023, Japan and Saudi Arabia established the KSA-Japan Lighthouse Initiative for Clean Energy Cooperation. The initiative aims to showcase both countries' leadership in clean energy projects and sustainable advanced materials, as well as ensure the resiliency of the supply chain.[272] The partnership will develop projects that guide clean energy transition, focusing on areas such as hydrogen and ammonia, among others.[273]

Transportation Costs

The cost of transporting and distributing hydrogen depends on the amount moved, the distance, and the method of transportation. For instance, to transport 500 million tons, the cheapest option today involves hydrogen using repurposed gas pipelines and repurposed storage sites, when technically and economically feasible. Conversely, any supply chain involving shipping hydrogen transformed into ammonia will be more expensive. The CAPEX investments in infrastructure to construct a global ammonia supply chain could reach $5 trillion.[274]

Canada is attempting to carve out a market space for hydrogen, albeit currently as ammonia, transported via shipping from both its west and east coasts so as to be a player in both European and Asia-Pacific markets when these mature. Canada could see its ammonia industry transition to hydrogen once the market has developed and the price of hydrogen production and shipping has decreased.[275] In August 2022, a Nova Scotia company signed an agreement to export 500,000 metric tons of green ammonia per year to Germany, while Alberta's fossil fuel industry is advancing plans to send blue ammonia to Asian customers via Canada's west coast.[276]

Pipelines, particularly repurposed ones similar to those used by Gasunie in the Netherlands, offer low-cost local distribution. In areas lacking such infrastructure or where smaller quantities are needed, trucks for both liquid and compressed gaseous hydrogen can be utilized. Pipelines are generally less expensive than electric transmission lines and are most cost-effective over short distances, especially when they can be converted from existing structures. For longer distances, transporting liquid hydrogen (alternatively ammonia) is more cost-effective, while the expense of trucking gaseous hydrogen grows significantly with distance. The cost of moving gaseous hydrogen by pipeline also escalates more quickly than liquid transportation (using carriers like green ammonia or methanol). The levelized transportation cost, including conversion and reconversion, varies based on transportation mode, distance, and volume. It can range from $0.1/kg to $1.5/kg for up to approximately 300 miles overland, and $1/kg to $1.5/kg for green ammonia by sea. Storage costs for gaseous hydrogen are between $0.25/kg and

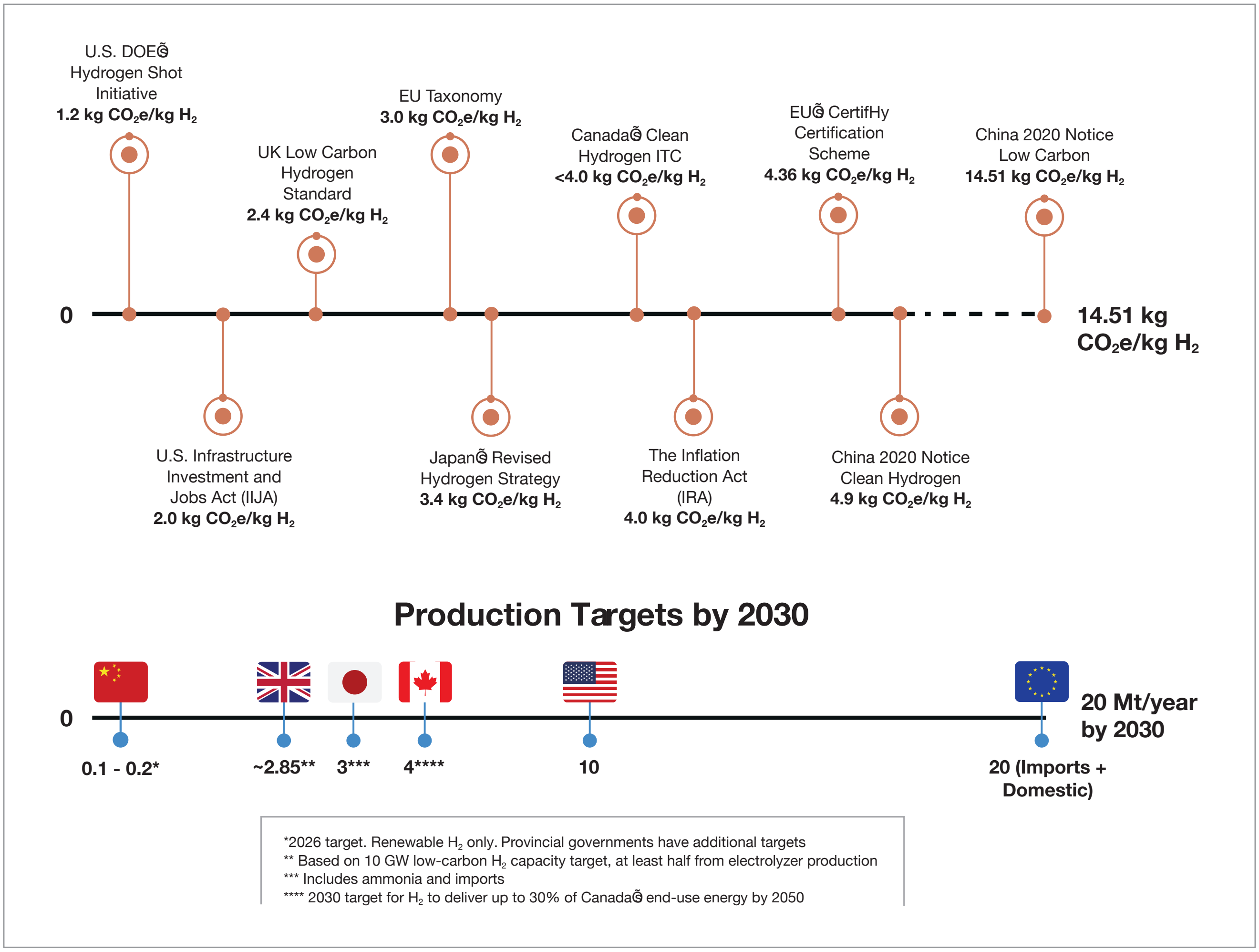
$1.5/kg, and for liquid hydrogen, they are between $2/kg and $3/kg. At fuel stations, costs are currently about $4.5/kg to $5.5/kg but are expected to decrease over time as throughput increases.

> **Hydrogen will struggle to become market-viable by 2030 without government support, as projects of meaningful size will lack the investments needed because of a lack of demand.**

Government Incentivization

Hydrogen will struggle to become market-viable by 2030 without government support, as projects of meaningful size will lack the investments needed because of a lack of demand. As shown in Figure 43, recent investments by the United States and Europe lead the way and demonstrate that hydrogen is being taken seriously. The IEA notes that "large amounts of government funding are being made available through schemes such as the U.S. Hydrogen Production Tax Credit, the EU Important Projects of Common European Interest, and the UK Low Carbon Hydrogen Business Model."[277] It seems likely that with

Figure 43. Definitions of clean hydrogen and 2030 production targets by region



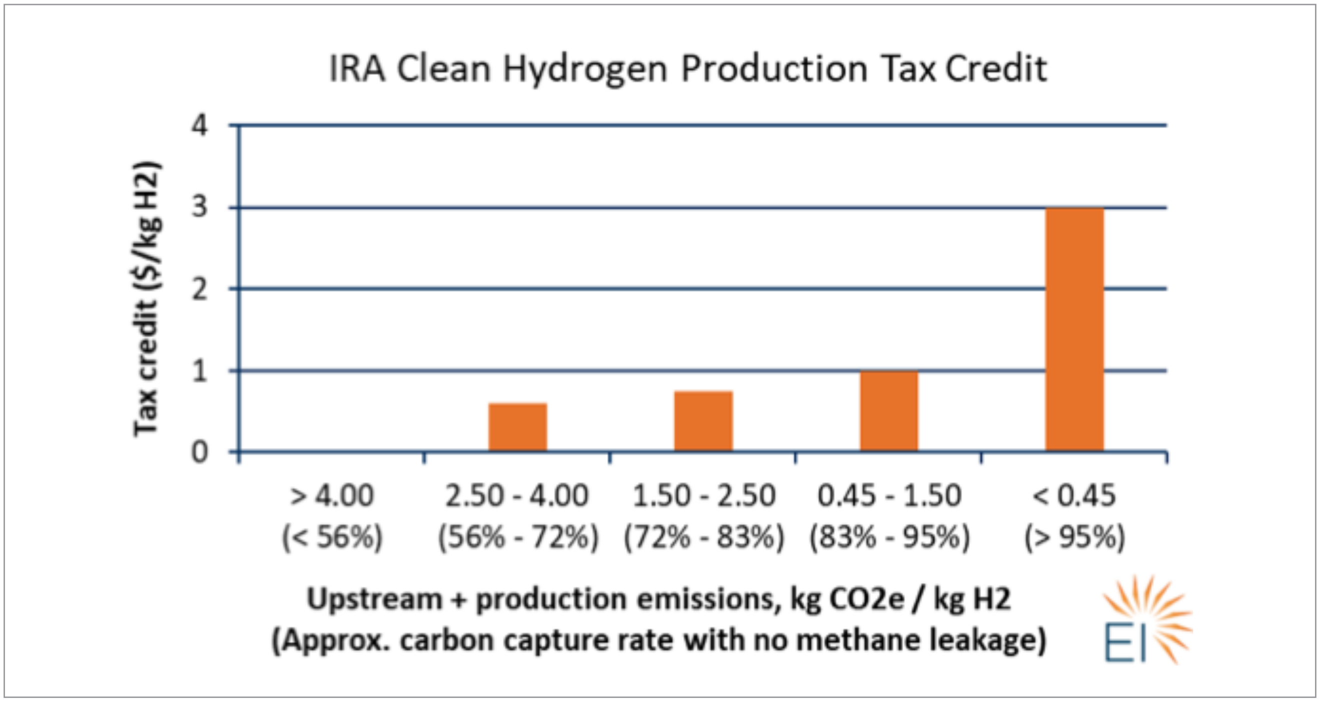
Source: EFI Foundation, Hydrogen Market Formation: An Evaluation Framework, https://efifoundation.org/wp-content/uploads/sites/3/2024/01/H2-Market-Evaluation-FINAL-with-cover.pdf more government support, private investors will gravitate toward green hydrogen as CAPEX costs fall and as carbon emissions pricing takes hold in more countries.

The United States, known for its pragmatic regulatory approach and business-friendly policies, is emerging as a potential competitor or supplier to Europe's domestic clean energy demand. With the United States' dynamic approach to energy regulation, not only could its exports of clean hydrogen compete with European domestic supply but the country could become a significant exporter to other markets. This potential competition between the two major Western economies underscores the global nature of the energy transition and the strategic importance of positioning in the emerging clean energy market.

In the United States, 90% of annual hydrogen production is dedicated to ammonia facilities (for fertilizer production) and oil refineries.[278] To create more hydrogen demand, the United States included hydrogen provisions in the Inflation Reduction Act of 2022 (IRA). Specifically, the IRA has provisions and tax credits to produce green hydrogen. Figure 44[279] details the IRA clean hydrogen production tax credit (45V) based on tax credit per kilogram of hydrogen produced.

The White House released 45V Guidance in December 2023, and the guidelines are based on three pillars. Per the guidance, the "regionality" pillar requires the renewable energy must be produced close to the point of use. The pillar known as "additionality" would require any clean power used to come from new, not currently operating, generation facilities. The final requirement, "hourly time matching," calls for the hydrogen production to be matched hour by hour with clean-energy production, rather than using annual matching of production.[280] In December 2023, the Internal Revenue Service of the U.S. Department of the Treasury issued proposed regulations to amend the income tax regulations under sections 45V and 48 regarding the production of hydrogen.[281] As of

Figure 44. IRA clean hydrogen production tax credits



Source: Dan Esposito and Hadley Tallackson, "The Inflation Reduction Act upends hydrogen economics with opportunities, pitfalls," Utility Dive, 2022, https://www.utilitydive.com/news/the-ira-will-accelerate-electrolyzed-hydrogens-future-heres-what-that-me/632925/.

the writing of this analysis, the 45V credit Notice of Proposed Rulemaking (NOPR) for the production of clean hydrogen remains under Department of Treasury analysis following the public “comment period," with final rules to follow.[282] Many have argued that the NOPR requirements will impede hydrogen market development in the United States.

General eligibility for the 45V tax credit in the NOPR:[283]

- Allowable for clean hydrogen produced at a qualified clean hydrogen production facility during the 10-year period. Construction must begin before 2033.
- Life cycle “well-to-gate” GHG emissions rate may not be greater than 4kg CO2/eq/kg H_2, as determined by the recently updated Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET) model, known as the 45VH2-GREET Model.
- A facility cannot apply for both 45V and 45Q (a tax credit for CCUS associated with blue hydrogen production).
- Storage of hydrogen before sale or use would not disqualify such hydrogen from being considered produced for sale or use, as defined by the proposed rules.
- Power used to produce hydrogen.
    1. Must be sourced from generation that began commercial operation no more than three years before the hydrogen plant is placed into service (known as the “additionality” requirement). For an existing facility modified or retrofitted to produce qualified clean hydrogen, the facility must be in service before January 1, 2023; the facility may establish a new date following a retrofit in the fair market value of used property is not more than 20% of the facilities total value.
    2. Must be annual; matched with clean power generation until 2028, when it must transition to hourly matching.
    3. Must be sourced from the same region as the hydrogen production facility (known as the “regionality” requirement).

Calculation of 45V tax credit amount

- Credit for the taxable year is equal to a percentage of:
    - $3 per kilogram of hydrogen produced, adjusted for inflation, if prevailing wage and apprenticeship requirements are met, and
    - $.60 per kilogram of hydrogen produced, adjusted for inflation, if prevailing wage and apprenticeship requirements are not met,
- The applicable percentage of $3 (or $.60) per kilogram, set by statute, is based on the life cycle GHG emissions rate:
    - 20% if the rate is not greater than 4 kg $CO_2e/kg\ H_2$ and not less than 2.5 kg $CO_2e/kg\ H_2$
    - 25% if the rate is less than 2.5 kg $CO_2e/kg\ H_2$ and not less than 1.5 kg $CO_2e/kg\ H_2$
    - 33.4% if the rate is less than 1.5 kg $CO_2e/kg\ H_2$ and not less than 0.45 kg $CO_2e/ kg\ H_2$
    - 100% if the life cycle GHG emission rate is less than .45 kg $CO_2e/kg\ H_2$
- Credit amounts will be rounded to the nearest 0.1 cent.

Box 7. Hydrogen hubs in the United States

The United States announced in October 2023 that $7 billion of investment would go to developers around the country to build hydrogen hubs. The initiative is aimed at jump-starting the development of a hydrogen industry and associated infrastructure that will produce and deliver hydrogen fuels through a network of green hydrogen producers. The seven hydrogen hubs will be the first in a national network of green hydrogen producers, consumers, and connective infrastructure that also supports the production, storage, delivery, and end-use of green hydrogen. Additionally, the United States set aside $1 billion for a Clean Hydrogen Electrolysis Program, which aims to reduce the costs of hydrogen produced from clean electricity.[284]

Additionally, some individual states are moving forward with hydrogen tax credit plans. Illinois and Colorado created their own green hydrogen end-use tax credits, while California announced in August 2023 that it would produce a hydrogen market development strategy based on its own incentives for zero-emissions vehicles.[285]

In terms of government funding, the largest schemes are IPCEI3 in Europe (10.6 billion euros [$11.53 billion] granted in the first two rounds) and the production tax credits (45V) and credits for carbon capture and storage (45Q) in the U.S. In Japan and South Korea, funding has supported infrastructure buildout (e.g., refueling stations, liquid hydrogen value chain in Japan), whereas hydrogen clusters have received government funding in China.[286]

Europe has made meaningful progress toward its decarbonization goals while centering hydrogen as a key component. It has also experienced a profound destabilization event in the form of Russia-Ukraine war, giving insight into how more immediate crises may affect market evolution. In Europe, the approach is different from that of the United States. The European Commission and key member states are actively working to accelerate the growth of the hydrogen market. Collaborations are underway, with countries like Germany and the Netherlands (potential significant consumers of green hydrogen) partnering with Spain and Portugal (potential large-scale producers.) Such collaborations aim to streamline investments and infrastructure development.

Europe has introduced regulations that specify targets for clean hydrogen uptake to stimulate demand and create opportunities for producers and traders to secure offtake contracts in the region.[287] In November 2023, the EU approved a framework to decarbonize gas markets, promote hydrogen, and reduce methane emissions. The applicable hydrogen directives from the laws set investment rules and regulations to determine this new market structure. In adopting unbundling rules for hydrogen network operators that are in line with best practices in the gas and electricity market, countries like Germany can exempt gas grid operators from an obligation to invest in hydrogen grids through a separate company if they have less than 100,000 customers.[288]

In its strategic vision, the European Union is recalibrating the equilibrium between state interventions and market forces. This recalibration heralds a new era where governments are more proactive, steering the direction of strategic energy initiatives. Historically known for its open market dynamics, the EU is gradually evolving into a posture that intervenes more aggressively in the open market, working to redress the balance between states and the market. This shift is characterized by member states aggressively trying to strike a balance between governmental control and the free market. One of the most evident manifestations of this change is the attempt to regulate and control open market price discovery processes, especially those that pertain to retail markets. Such regulatory shifts are not without their challenges and implications. They represent a fundamental change in the way the EU views and interacts with its market dynamics, potentially impacting various sectors, including energy.

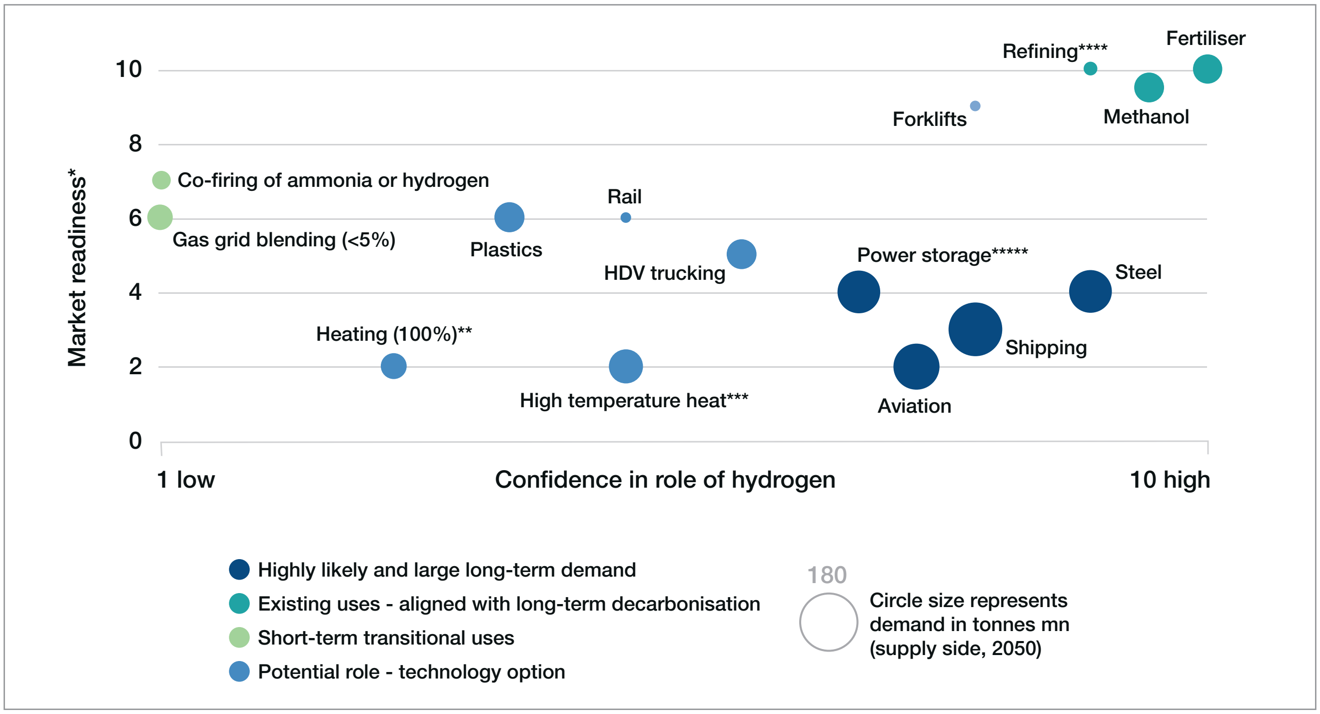
However, the path is not devoid of challenges. The plethora of funding and support programs, each with its specific targets and requirements, has led to a complex landscape. The European hydrogen market stands at a crossroads. With the confluence of innovation, policy frameworks, and market dynamics, hydrogen is poised to be a linchpin in Europe's sustainable energy matrix. The American hydrogen market is starting to become clearer, with government intervention from the IRA taking effect. How the market will materialize over the next five to 10 years is dependent upon how policy is translated to business development and demand creation.

The Industrial Transition to Hydrogen

For green hydrogen to increase demand and procure a larger share of energy production, it needs to be able to be utilized in different industries and technologies at higher amounts. In analyzing the industry and technologies present and making educated predictions about what will happen in the future, an order is identified in which low-carbon hydrogen is likely to be prioritized across various industries. Figure 45 shows that such a sequence emerges as a rational pathway for the development of the market and subsequent price setting.[289]

The most likely top priorities in most places will be using green ammonia in the fertilizer industry, clean hydrogen as a raw material for refineries and petrochemical plants, and as a decarbonization option providing heat for sectors like steel, cement,

Figure 45. Potential industrial destinations for hydrogen



Source: Financial Times, "Lex In Depth: The staggering cost of a green hydrogen economy," May 28, 2023, https://www.ft.com/content/6e22930b-a007-4729-951f-78d6685a7514.

aluminum, and paper production. Other priorities will be hydrogen used for maritime shipping and aviation, followed by land-based transportation, and eventually for electricity and heating purposes. While Figure 45 provides a detailed hierarchy of these segments, it does not imply that lower priorities must wait for higher ones to be fully developed.

However, location-dependent, higher-priority sectors could receive more strategic focus, business development efforts, and investment. Those considered top priority because of their significant potential to reduce direct and indirect greenhouse gas emissions will be addressed first. These high-priority areas are crucial because without transitioning energy-intensive industries from fossil fuels to green hydrogen, achieving the goals of the Paris Agreement will be unattainable.

Priority 1: Chemicals and processes. The primary focus is on replacing gray hydrogen in refineries, petrochemicals, fertilizers, and steel manufacturing to reduce GHG emissions.

Priority 2: Shipping and aviation. Opportunities for clean hydrogen in shipping come through clean ammonia and methanol. In aviation, hydrogen is essential for producing SAF in hydro-treated vegetable oil plants.

Priority 3: Land transportation. Hydrogen might scale up post-2030 but is likely to remain a niche market for the foreseeable future. The initial targets, crucial for meeting the Paris Agreement goals, will require millions of tons of green hydrogen, particularly in energy-intensive industries transitioning from fossil fuels to hydrogen-based processes.

In some regions, like the United States, the highest priority will likely be replacing gray hydrogen with clean hydrogen in refineries, petrochemicals, fertilizers, and steel or cement production processes to cut direct and indirect greenhouse gas emissions notably and to explore the possibilities of exporting a “green” product (i.e., steel or cement made with green hydrogen) over exporting hydrogen molecules. Thus far in Japan, it appears that power generation and transportation demand sectors will be a focus.

Chapter 5: Conclusion

The conversation about hydrogen has grown dramatically in recent years. However, focusing on the highest-value uses of hydrogen is key for success. This analysis seeks to inform policymakers and other stakeholders that while a hydrogen market may take years to form, there is much that can be done to incentivize the emergence of a market structure. Promoting hydrogen demand and focusing on national-level policies, bilateral agreements, and regional development are all steps that can lead the way to a global hydrogen future.

Insights into Hydrogen Price Formation and Value Chains

Comprehending the international framework and the historical factors shaping the natural gas industry and its market evolution provides valuable insights into establishing a hydrogen market.

Historically, the LNG business offers a parallel, with its value chains being tightly integrated. These value chains were characterized by high trust levels with risk sharing between producers and consumers, long-term contracts, and cross-ownership in key segments. Beginning in the 2000s, the LNG business began to diversify its value chains, driven by market pressures, governmental regulations, and global commodity traders that further liberalized the LNG markets. The arrival of U.S. LNG in 2016 continued to allow for more market flexibility.

In the United States and Canada, due to market liquidity (the ready availability of gas buyers and sellers), competition has come mainly from other gas suppliers, and the price is set by gas-to-gas competition, with the long-term floor and ceiling prices set by alternative fuels (e.g., coal and fuel oil). In these markets, pricing is established primarily on short- and medium-term gas supply/demand fundamentals. Transparent gas prices (i.e., prices that are both accepted by the market as valid and available to the market on a timely basis) are provided through gas price surveys published as daily and monthly indexes by third parties and through the prices of publicly traded commodity futures markets.

In the Middle East, natural gas markets evolved from what had historically been the flaring of associated gas from the production of oil into the local use of this low-cost energy source to produce electricity, water, and attract industry (i.e. direct foreign investment), then ultimately evolving into what has become a key export from the region through either pipeline gas or LNG sales. As both local and global demand for natural gas has grown, an interconnectivity of markets occurred, and many non-associated gas resources within the region have or are also being developed. While natural gas is not completely fungible, this interconnectivity of markets has shaped the overall pricing of natural gas and hastened the evolution toward global liquidity.

The underlying principle for European and Japanese gas pricing (which established the foundation for Asian LNG pricing practices) for many years was that the market price for gas is set by competing energies at the burner tip, primarily and preferentially oil products. In periods of supply surplus, prices below oil parity would be expected to cause a reduction in new gas developments, exerting a supply-driven price rise over the long run. Gas prices above oil parity, on a thermal or MMBtu basis, would result in a shift from gas to alternative fuels, thereby exerting a demand-driven price drop. Over time, gas prices would theoretically gravitate toward oil parity.

The oil industry's transition from the exploitation phase of the 1990s to the investment surge in the early 2000s exemplifies the lag between investment signals and actual capital expenditure and production capacity increases. This industry also experienced a decline in returns on capital employed due to cost overruns and delays starting in 2006. Given its similar early-stage development, green hydrogen's trajectory could mirror both the oil and natural gas sectors. The renewable energy sector, which is comparatively more straightforward and mature, took more than two decades to experience significant growth, suggesting that the hydrogen industry may have a long journey ahead.

The evolving clean hydrogen market will likely draw from the current LNG models but will replace gas supply with electricity from renewable sources like solar and wind. Given the nascent nature of the hydrogen market, early players might prefer to manage the entire value chain to mitigate risks, similar to the approach taken by Saudi Arabia in NEOM's hydrogen infrastructure. The hydrogen market's development will be multiphase, like the LNG industry. However, the hydrogen value chain involves a broader range of corporates compared with LNG, complicating formation and cohesiveness.

Broadly speaking, green hydrogen is not yet competitive in the open market. Its adoption and proliferation will depend on two primary factors: industries that recognize the value of renewable energy and are willing to pay a premium for it, and governmental support in the form of subsidies and tax incentives. The expectation is that as technology advances and economies of scale kick in, the cost of green hydrogen production will decrease, making it a more viable and competitive energy source in the future.

The speed and direction of each of these markets will be determined by how the price of hydrogen forms in the future and, more specifically, what factors will influence this price formation.

Insights Into Future Hydrogen Pricing and Costs

In 1999, many were convinced oil prices would stay low forever and dubbed it a $10 oil world. However, when The Economist was reporting on BP and Shell's belief that prices would indeed stay low for the near future, the then-running exploitation phase was coming to an end. Shortly thereafter, oil prices started to rise, which led to a spike of $147 per barrel of crude oil in 2008. But it took the industry at least four years to accept this phenomenon and to understand that the investment phase had started and a new super cycle was happening. This is highly likely to happen again once U.S. shale can't grow any longer, which is expected to occur between 2026 and 2028.

In 2005, the consensus view in the United States was that the technically recoverable shale gas—the amount that can be extracted using current technology and industry practices—was around 140 trillion cubic feet (Tcf), and by 2010 it had risen to 583 Tcf. Currently, it stands at 862 Tcf.[290] Also in 2005, predictions of the long-term prices at Henry Hub were $5.98 (2005 dollars/million cubic feet) for 2010-2020 and $6.42 for 2021-2030.[291] With this price, production started in earnest around 2005 because the prediction was that it would grow rapidly. Even with this growth, the United States would remain an LNG importer.

According to a U.S. Energy Information Administration forecast from 2010, shale gas would supply 25% of U.S. domestic demand, but imports would still be needed.[292] Hence in the first years of the shale revolution, none of the super majors were interested in shale as it was marginal and too expensive to develop. The Kashagans, Sakhalins, Brazilian subsalt developments, and Gorgons of this world were far more interesting to developers. The independent shale operators had little concern about super majors taking shale market share.

The following year, after the EIA's forecast, British Gas Group and Cheniere announced that Sabine Pass, in Port Arthur on the border between

Louisiana and Texas, would become the first North American LNG export project since Kenai in Alaska in 1969. The agreement for 3.5 Mtpa of LNG for 20 years underpinned the first 4.5 Mtpa liquefaction train at Sabine Pass. Within five years, the entire market outlook for LNG in the United States dramatically changed.

From the early to mid-2000s, the LNG sector moved away from its traditional, tightly knit value chains. Market pressures and new governmental regulations drove this change. The industry saw a growing demand for more flexible contract structures, leading to the gradual phasing out of destination clauses and the introduction of innovative LNG pricing mechanisms. These changes were not merely contractual; they represented a fundamental shift in how the LNG business operated. The industry began to explore arbitrage opportunities between different regional markets, leading to the emergence of LNG aggregators. These aggregators were pivotal in optimizing global supply chains, aligning global supply with demand more efficiently.

Many clean hydrogen projects are in the development phase. A race between a new investment phase (in oil and gas) and a compelling substitution phase (in renewables including green hydrogen) is starting, and it is highly uncertain which one will prevail. At best, buying time is characterized by low but stable economic growth for the rest of the decade so that annual energy demand growth stays within the lower bounds of the forecasts made for the years ahead.

In response to the changing environment, corporations have diverged in their strategies. Some are cutting investments in renewables to preserve capital, while others are restructuring their portfolios or revising their renewable energy source strategies to ensure profitability. A few, with strong balance sheets, are accelerating renewable projects. However, there is a risk of project delays, cancellations, and impairments on legacy projects due to cost pressures.

The share price performance of companies like Ørsted reflects the industry's volatility. Ørsted's share price, which had seen significant growth, has halved from its peak because of cost, funding inflation, and high leverage. Despite this, there is optimism for a more disciplined growth strategy and higher project return targets. The industry's evolution mirrors the U.S. shale industry, where a shift from growth to profitability was driven by shareholder demands.

The oil majors are revisiting their renewable energy strategies, moving away from power assets to focus on hydrogen, CCUS, biogas, and biofuels. This shift aligns with their existing hydrocarbon businesses and promises higher returns. Policy initiatives in Europe and the U.S. are supporting this transition, but the same level of support is not yet seen globally.

Moreover, companies must be allowed to develop the new clean hydrogen value chains in a way comparable to the value chains that were organized in the 1990s and 2000s. Initial negotiated deals with a few participants, along the value chain, could lower the credit risk and better allocate profits and build trust.

Given the many uncertainties, challenges, and risks, it is better to describe the clean hydrogen endeavor as a new industry that is currently in the developmental phase. Until early last year, many people involved in this emerging industry segment were perhaps overly enthusiastic instead of focusing on overcoming the many challenges.

During the summer of 2023, attitudes reset, notably because of the supply of very cheap green electricity to electrolyzers and the cost inflation aspects in every segment along the clean hydrogen chains. Governments have needed to reset their agendas, rewrite their laws and directives, and accept that many of the hard 2030 climate objectives regarding clean hydrogen are challenging to achieve. This is a normal market consolidation that occurs with nascent technologies, and governments must continue to support burgeoning technology implementation and find ways to connect with industry to develop new viable routes that are affordable, practical, and financeable.

Key Findings

The need to invest in clean energy technologies is ongoing. No single option enables deep decarbonization of every sector. According to the International Energy Agency (IEA), despite the proliferation of initiatives to reduce GHG emissions, these efforts have had limited success. This underscores the need to accelerate the development and deployment of low-carbon dioxide (CO_2) emissions technologies—and for support from the developed world for decarbonization efforts in the developing world.

The key findings are organized around the dimensions of: **Opportunities for Hydrogen Demand, National Policies and International Regulations, and Hydrogen Market and Price Formation.**

Opportunities for Hydrogen Demand

- Increasing demand from Europe, Asia, and North America will drive the growth of a global hydrogen market.
- The MENA region has the opportunity to be a significant exporter of hydrogen.
- Using hydrogen and derivatives (ammonia, methanol) in transport, as carriers of energy, could contribute to the growth in demand needed to develop regional and global markets.
- Both technological advancement and policy support are necessary to make hydrogen pathways economically competitive.
- While much has been done in the United States (i.e., the Inflation Reduction Act of 2022) and internationally (REPower European Union) to incentivize the supply of hydrogen, the policy challenge remains on the demand side, and reducing the cost of producing clean hydrogen is imperative.
- When considering decarbonization strategies and technological advancements in hard-to-abate sectors, aspirations and realistic technology-development timelines need to be contrasted against net-zero goals for the most effective use and investment of capital.
- Stakeholders in the hydrogen industry agree that the world's largest fossil fuel-producing nations can lead the decarbonization of the industrial sector, particularly using clean hydrogen in the ammonia, refining, and methanol sectors.
- Hydrogen exports can be better facilitated by simple framework agreements among market participants—such as for hydrogen hubs and EU valleys—that clarify the roles necessary to build infrastructure for hydrogen export.

National Policies and International Regulations

- Setting targets for hydrogen production without complementary policies to spur demand can lead to incorrect assumptions and create a confusing investment environment for potential developers.
- Bottom-up project developments (led by industry) combined with top-down strategies and policy mechanisms (led by governments) can facilitate the rapid scale-up of a global hydrogen market.
- Global data standardization applied on a regional basis is essential for hydrogen market development. For this, a comprehensive database of energy statistics—like what exists for oil and gas markets—is needed. The database should use nationally sanctioned data to produce fair assessments of monthly production and consumption globally.
- Offtake still depends on policy guidance, and many stakeholders believe governments need to do more to move hydrogen beyond its initial stages as an energy commodity to create the exponential growth needed for market development.
- Regardless of the policy used to incentivize hydrogen value chains, developers and industry representatives have indicated that they need regulatory certainty to invest and commit to hydrogen—especially within niche markets like green steel, sustainable aviation fuels (SAFs), and shipping with hydrogen derivatives (e.g., ammonia, methanol).
- Beyond subsidies, carbon pricing mechanisms could encourage a global hydrogen market, but it will ultimately come down to cost reduction and regional price harmonization (reciprocity).
- For green hydrogen projects, water access and requirements for production can be effectively managed if intentional sourcing, siting, and efficient use is prioritized.
- In multiple parts of this analysis, safety issues are raised about hydrogen. They include flammability and leaks, infrastructure embrittlement, and storage pressure, among other concerns for human safety.

Hydrogen Market and Price Formation

- Transparent pricing is paramount in the hydrogen market as it fosters trust and facilitates efficient transactions. Similar to how Henry Hub serves as a benchmark for natural gas and Brent for oil, a standardized pricing mechanism for hydrogen enhances market liquidity, aids in risk management, and promotes fair competition, ultimately driving innovation and investment in the burgeoning hydrogen economy.
- Global hydrogen market formation will require a reframing of hydrogen and derivatives as carriers of energy (versus as chemical products) and a tool to build upon existing energy systems. From a market context, hydrogen price formation can be viewed as scaling up the market of a smaller specialty chemical to a new globally traded fuel, which will take time.
- How the market will materialize over the next five to 10 years is dependent upon how policy is translated to business development and demand creation. Price discovery informed by clear policies will expedite FID, manage costs, and mitigate risk.
- Hydrogen pricing mechanisms will need to insulate both producers and consumers from volatility risk—which is most prevalent at the early stages of development, where risk sharing between supplier and consumer can be beneficial and guarantee returns in a nascent but fast-growing market.
- The financial industry will require non-concessionary investments that demonstrate value across the supply chain. Policies such as tax incentives may help to make hydrogen cost-competitive. Equity markets or venture capital could facilitate financing mechanisms to help near-term hydrogen projects get off the ground.
- The financing of early technology or first-of-a-kind projects is complex and can be expensive, thus balancing the potential for technological advancement along with the inherent uncertainty and capital-intensive nature of such pioneering ventures is crucial. Therefore, a government backstop, through sovereign guarantees or blended financing, can mitigate risk and provide more investment certainty as the clean hydrogen market scales up.
- Access to metals and minerals for electrolyzer and fuel cell production, in addition to the cost of electricity, can be a large part of determining hydrogen costs and how soon these technologies can be used at the scale necessary for decarbonizing hard-to-abate sectors.
- For some countries, hydrogen market formation may follow a path like natural gas and LNG as markets transition from domestic to regional. The hydrogen market's development will possibly be multiphase, like the LNG industry. However, the hydrogen value chain involves a broader range of corporates compared with LNG, complicating formation and cohesiveness.
- Hydrogen will struggle to become market-viable by 2030 without government support, as projects of meaningful size will lack the investments needed if there is a lack of demand.
- The burgeoning green hydrogen market will likely draw from the current LNG models but will replace gas supply with electricity from renewable sources like solar and wind. Given the nascent nature of the hydrogen market, early players might prefer to manage the entire value chain to mitigate risks.

Recommendations

Based on the findings, this report provides recommendations for decision-makers to clarify a route for hydrogen in the global energy mix and to foster growth of a hydrogen economy.

Based on the findings, this report provides recommendations for decision-makers to clarify a route for hydrogen in the global energy mix and to foster growth of a hydrogen economy. The recommendations are organized around the dimensions of **Opportunities for Hydrogen Demand, National Policies and International Regulations,** and **Hydrogen Market and Price Formation**; however, many of them are cross-cutting and can be found throughout this analysis as applicable in several areas.

Governments, international bodies, and industry initiatives have varying emphases on hydrogen as a strategy for meeting all needs and goals, and substantial tasks remain. All stakeholders should accelerate efforts and turn their commitments into detailed policies and actions.

Opportunities for Hydrogen Demand

By implementing these recommendations, government officials can play a crucial role in fostering the growth of the hydrogen economy, promoting sustainable development, and ensuring their country's competitiveness in the global energy market.

- **Policy framework development:** Formulate comprehensive policies that support the transition of hydrogen from a chemical commodity to a key energy carrier. This may include establishing regulatory frameworks, incentives, and funding mechanisms to encourage investment in hydrogen infrastructure, research, and development. Governments should foster a widespread global hydrogen transition through not only domestic incentives but also through new regulations and the classification of hydrogen as an energy carrier. In this effort, governments should promote hydrogen as a commercial fuel.
- **International collaboration:** Foster partnerships with key stakeholders, both domestically and internationally, to capitalize on the increasing demand for hydrogen in Europe and Asia. Stakeholders should explore opportunities for collaboration on research, technology transfer, and market development to ensure that their country remains competitive in the global hydrogen market.
- **Export potential:** For the MENA region, recognize and leverage the region's unique opportunity to become a significant exporter of hydrogen. Develop strategic partnerships with countries in the region to facilitate the production, storage, and transportation of hydrogen to global markets. This may involve supporting infrastructure projects and trade agreements that promote the export of hydrogen and related products. Capitalizing on the MENA region's potential can foster a transformative shift toward hydrogen as a key export commodity. By forging strategic alliances with MENA countries,

nations can unlock vast opportunities for the production, storage, and transportation of hydrogen to global markets. This entails nurturing partnerships aimed at developing robust infrastructure and establishing trade agreements that facilitate the seamless flow of hydrogen and its derivatives worldwide. Such collaborations not only position the MENA region as a pivotal player in the emerging hydrogen economy but also contribute to regional economic growth and energy security. By harnessing the abundant renewable resources, natural resources and sequestration potential, and strategic geographical location of the MENA region, stakeholders can spearhead the transition.

- **Diversification of national and regional energy portfolios:** Encourage the use of hydrogen as a commercial fuel and promote its role as an energy carrier in addition to its traditional applications in industries such as fertilizers. Implement policies that incentivize the adoption of hydrogen-based technologies in sectors such as transportation, industry, and power generation to stimulate demand and drive market growth.
- **Technology and innovation support:** Provide support for technological advancement in hydrogen production, storage, and utilization through funding programs, research grants, and collaboration with academic institutions and industry partners. Create an enabling environment for innovation by removing regulatory barriers and promoting public-private partnerships in hydrogen-related research and development initiatives.
- **Diversified utilization of clean hydrogen:** Encourage the utilization of green hydrogen in various industries and technologies to increase demand and secure a larger share of energy production. Promote its integration into existing supply chains and infrastructure. Similar to the global policy rush after the Inflation Reduction Act of 2022, the global establishment of production and demand programs is a positive step toward a global hydrogen market.

By implementing these recommendations, government officials and international organizations can create an enabling environment for the development of a thriving global hydrogen market, characterized by investment confidence, policy coherence, and sustainable growth.

National Policies and International Regulations

By implementing these recommendations, government officials and international organizations can create an enabling environment for the development of a thriving global hydrogen market, characterized by investment confidence, policy coherence, and sustainable growth.

- **Integrated policy frameworks:** Develop holistic policies that set targets for hydrogen deployment while also incorporating complementary measures to stimulate demand. Ensure that policies are well aligned with market realities and provide clear guidance for investors to avoid confusion and uncertainty.
- **Synergistic approaches:** Encourage a combination of bottom-up project developments driven by market forces and top-down strategies supported by policy mechanisms. Foster collaboration between public and private sectors to create synergies

and accelerate the scale-up of the global hydrogen market. By embracing this dual approach, stakeholders can leverage the agility and innovation inherent in market-driven initiatives while harnessing the guiding influence and support of targeted policy interventions. This synergy between bottom-up and top-down strategies not only ensures a diverse array of projects tailored to local needs and market conditions but also fosters a conducive environment for sustainable growth and development. Moreover, fostering collaboration between the public and private sectors is crucial for creating synergies and accelerating the scale-up of hydrogen technologies. Public-private partnerships enable the pooling of resources, expertise, and capabilities, facilitating the deployment of innovative solutions, the development of critical infrastructure, and the expansion of market reach. There is much that governments can do to incentivize early technology or first-of-a-kind projects. Given the particular and capital-intensive nature of such projects, balancing the potential for technological advancement along with the inherent uncertainty of such pioneering ventures is crucial. Therefore, a government backstop, through sovereign guarantees or blended financing, that can mitigate risk and provide more investment certainty as the clean hydrogen market scales up is recommended.

- **Data standardization and sharing:** Advocate for global data standardization in the hydrogen market, similar to the Joint Organization Data Initiative (JODI) for oil and gas markets. Promote regional cooperation to establish comprehensive databases of energy statistics, enabling fair assessments of production, consumption, and market trends. This initiative would not only facilitate the exchange of accurate and reliable information but also enhance market transparency and integrity. By fostering collaboration among neighboring countries and regional organizations, these databases serve as valuable tools for policymakers, investors, and industry players to make informed decisions, identify emerging opportunities, and address challenges collectively. Embracing global data standardization and regional cooperation in the hydrogen market creates a more level playing field, fosters trust, and unlocks the full potential of hydrogen as a clean and sustainable energy solution on a global scale.
- **Establish and maintain clear, accurate and comprehensive methodologies for regulatory certainty:** Through an organization like the International Organization for Standardization (ISO), establish uniform definition criteria for hydrogen (clean hydrogen, low-carbon hydrogen). The need for agreement on and standardization of emissions across supply chains is illustrated in this analysis along with a call for focus on incentive mechanisms for further investment. Ensure regulatory certainty to instill confidence in investors and industry stakeholders. Develop stable and predictable regulatory frameworks that support long-term investments in hydrogen value chains—beyond just providing subsidies—to drive sustainable market growth. Enhance clarity around regulations and subsidies, particularly in niche markets like green steel, sustainable aviation fuels, and shipping with hydrogen and hydrogen derivatives. Clear regulatory frameworks and subsidies will incentivize industries to commit to hydrogen adoption.

The ISO offers a good model for addressing these issues. It has brought together industry and global experts to agree on the best way of doing things, from measurement standards to managing production processes. As a nongovernmental international organization, ISO has enabled trade and cooperation for almost 80 years. ISO standards are created through a multistakeholder process, initiated by those who use them and could bring together disparate and geographic-specific standards under a single umbrella. ISO does not decide when to develop a new standard but responds to a request from industry or other stakeholders such as consumer groups. Typically, an industry sector or group communicates the need for a standard to ISO through a national-level representative. Internally, ISO standards are developed by technical committees composed of experts from all over the world. These experts would negotiate all aspects of the standard. Making changes at the ISO to accommodate and conduct this mission or establishing a new organization for developing ISO-like standards would enable investors to make informed choices. It also would incentivize the industry to reduce emissions and/or utilize offsets. Transparent and consistent measurements would provide buyers with a clear differentiator.

- **Conduct energy reviews:** Perform regional and global analyses to develop a comprehensive hydrogen market road map through 2050. An appropriate entity (e.g., World Bank, regional development banks, IEA, or other multinational fora) should perform an integrated energy review and analyze hydrogen development as a new energy industry to develop a comprehensive energy security road map through 2050. This effort would provide a deep analysis of supply/demand options, infrastructure needs, and a detailed country/regional review of the implications of fuel switching (costs of natural gas and hydrogen versus oil and coal) for industry and power generation. The review also would examine costs, affordability, energy access, and pollutants associated with the range of fuel options. Lastly, an analysis of the potential crowding out of other decarbonization options and fuels that hydrogen would compete with or utilize in its production is needed. For example how would the production of blue hydrogen affect the supply and price of natural gas?
- **Foster regional MDB programs:** Multilateral Development Banks (MDBs) should make hydrogen as a source of energy development projects a priority for country development plans and for regions. Partnership programs such as the U.S. Agency for International Development 's Power Africa partnership utilize the collective resources of the private sector, international nongovernmental organizations, and governments to increase energy access and end energy poverty across sub-Saharan Africa. Empowering regional goals to advance inclusive, low-carbon economic growth that improves lives and powers health, education, and prosperity by adding hydrogen as a new energy source should be a global priority. Regional projects like this could do much to expedite global hydrogen market development.
- **Foster carbon pricing mechanisms:** With more purpose and financial sector support, explore the implementation of carbon pricing mechanisms to incentivize the adoption of hydrogen and reduction of carbon emissions. Consider the importance of cost reduction and regional price harmonization to ensure competitiveness and drive the growth of a global hydrogen market. Standardized methodologies for price determination minimize discrepancies, promoting fair competition and market stability. The evolution of carbon pricing mechanisms beyond limited regional application is something worthy of being followed and ostered.

Hydrogen Market and Price Formation

By implementing these recommendations, governments can play a crucial role in fostering the development of a robust and sustainable hydrogen economy, ensuring market stability, investment certainty, and alignment with climate goals.

- **Equitable hydrogen pricing mechanisms:** Develop hydrogen pricing mechanisms that ensure transparency of hydrogen price reporting that will enable better market formation and mitigate volatility risks to enhance confidence in project returns in the nascent but rapidly growing market. Consider risk-sharing arrangements between suppliers and consumers to facilitate market development. Transparent reporting of hydrogen prices enables market participants to make informed decisions, enhances market liquidity, and fosters investor confidence in the nascent yet rapidly growing hydrogen market. By establishing standardized methodologies for price determination and reporting, stakeholders can minimize discrepancies and promote fair competition, driving market efficiency and stability. Additionally, considering risk-sharing arrangements between hydrogen suppliers and consumers presents an effective strategy for mitigating investment risks and facilitating market development.

- **Identify realistic timelines:** When formulating decarbonization strategies, balance aspirations with realistic technology development timelines. Contrast aspirations against net-zero goals to effectively allocate capital and prioritize investments in hard-to-abate sectors. Institute a global convening, under the auspices of an international organization, such as the IEA or the International Energy Forum, that includes national energy reporting agencies, such as the EIA and The Institute of Energy Economics, Japan, to discuss the data collection needed to inform policymakers and stakeholders on hydrogen market and price formation. Through collaborative discussions, these forums can identify the data requirements necessary to inform policymakers and stakeholders about the evolving dynamics of the hydrogen market and facilitate informed decision-making on price formation and market development.
- **Access to resources:** Ensure access to metals and minerals for electrolyzer and fuel cell production and evaluate repurposing existing natural gas infrastructure for hydrogen use to mitigate risks of stranded assets as natural gas consumption declines. Governments and industry stakeholders must collaborate to secure a stable and sustainable supply chain for these critical materials, leveraging international trade agreements and fostering partnerships with resource-rich countries.
- **Infrastructure construction and repurposing:** As the global transition toward renewable energy accelerates, repurposing existing natural gas infrastructure for hydrogen use presents a pragmatic solution to mitigate the risks of stranded assets. By evaluating the feasibility of adapting pipelines, storage facilities, and processing plants for hydrogen transportation and storage, stakeholders can minimize economic disruptions and maximize the utilization of existing infrastructure. Maintaining strong safety standards is paramount in any repurposing program.
- **Government support for market viability:** Recognize the necessity of government support for hydrogen market viability, as projects may lack investments without sufficient demand. Translate policy objectives into business development strategies and demand creation initiatives. Governments play a pivotal role in bridging this gap by providing the necessary support and incentives to stimulate demand and create a conducive environment for market growth. One effective approach is to translate policy objectives into targeted business development strategies and demand creation initiatives. This involves aligning policy frameworks with market dynamics and industry needs, while also fostering collaboration between government agencies, industry stakeholders,

and research institutions. For example, governments can incentivize the adoption of hydrogen technologies through subsidies, tax incentives, and procurement programs, thereby stimulating demand and driving market uptake. Additionally, investment in infrastructure development, such as hydrogen refueling stations and distribution networks, can help overcome barriers and accelerate market growth. By leveraging policy tools to catalyze business innovation and market expansion, governments can unlock the full potential of hydrogen as a clean energy solution, driving economic growth, job creation, and environmental sustainability.

- **Price discovery and policy alignment:** Facilitate price discovery through clear policies to expedite final investment decisions, manage costs, and mitigate risks associated with hydrogen projects. By providing a stable regulatory framework and implementing mechanisms for pricing carbon emissions, governments can incentivize private sector investment in clean hydrogen infrastructure and technologies. Additionally, transparent market mechanisms such as auctions or competitive bidding processes can help to determine fair and competitive prices for hydrogen, fostering market confidence and attracting investment. Moreover, measures to standardize quality and certification requirements for hydrogen production and distribution can enhance market transparency and facilitate fair competition among industry players. Through proactive policy interventions aimed at facilitating price discovery, governments can create an enabling environment that accelerates the transition toward a hydrogen-based economy, driving down costs and increasing the competitiveness of hydrogen as a clean energy source.
- **Facilitation of hydrogen exports:** Simplify framework agreements between market participants to facilitate hydrogen exports, such as through hydrogen hubs in the United States and other regional initiatives like the EU valleys, which serve as promising models for facilitating hydrogen supply and demand. Clarify the roles and responsibilities of government agencies and the private sector in building infrastructure for hydrogen export. Governments play a crucial role in providing regulatory certainty, investment incentives, and support for research and development. Collaborative efforts between government and industry stakeholders are vital for accelerating the deployment of hydrogen export infrastructure, ensuring that it is economically viable, environmentally sustainable, and meets international quality and safety standards. As an example, in the United States the Export-Import Bank supports U.S. exporters of capital equipment and services. Loan guarantees not only support U.S. exports, but they can also help secure financing for international buyers who require extended-term financing. Medium- and long-term loan guarantees may be suitable for large-scale projects such as export of clean hydrogen technology or services. By fostering a conducive regulatory environment and promoting public-private partnerships, countries can unlock new opportunities for hydrogen exports, driving economic growth, enhancing energy security, and contributing to global decarbonization efforts.

Areas for Continued Research on Enabling Activities

Through research and analysis, it has become evident that further research is needed in three key areas not addressed in depth in this report, notably: mitigating water use in green hydrogen electrolysis and other forms of clean hydrogen production, developing a clean hydrogen workforce, and analyzing safety issues.

- **Water scarcity mitigation:** Analysis indicates that addressing the challenge of water scarcity in hydrogen production by promoting the adoption of water-efficient electrolysis technologies and encouraging the use of renewable energy sources requires further study. Of particular interest are investments in research and development initiatives aimed at reducing the water footprint of hydrogen production processes and exploring innovative solutions for water recycling and conservation.
- **Developing a clean hydrogen workforce**: Effective hydrogen workforce development initiatives are essential for equipping individuals with the specialized skills and knowledge needed to drive innovation, maximize efficiency, and ensure the successful integration of clean hydrogen technologies into our energy landscape. Researching cross-cutting environmental justice (EJ) issues also presents an opportunity to examine the unequal distribution of environmental burdens and benefits among diverse communities with this new workforce. An interdisciplinary approach that incorporates perspectives from environmental science, sociology, public health, and government policies could provide valuable insights into addressing these complex challenges.

  International and national oil companies are well placed to leverage experience in EJ issues and to train workforces and enable clean hydrogen technologies and a global market to take off. Comprehensive training programs and educational initiatives are essential for cultivating a skilled workforce capable of designing, implementing, and maintaining hydrogen infrastructure and technologies. From engineers and technicians to researchers and policymakers, a diverse range of professionals must be equipped with the specialized knowledge and expertise needed to drive innovation and address the complex challenges associated with clean hydrogen production, storage, distribution, and utilization. Moreover, fostering collaboration between academia, industry, and government entities is crucial for promoting knowledge exchange, advancing research, and accelerating the deployment of hydrogen solutions. Prioritizing hydrogen workforce development, opportunities for economic growth, and job creation ensures that the talent and capabilities necessary to realize the full potential of hydrogen as a clean and versatile energy carrier are possible.
- **Analyze safety issues:** In several parts of this analysis, issues of hydrogen safety are raised, including flammability and leaks, infrastructure embrittlement (pipelines and storage tanks), and storage pressure, among other human safety concerns. To address these safety concerns, extensive research and development efforts are needed to improve hydrogen technologies and establish robust safety standards and protocols. This includes advancements in materials science, leak detection technologies, safety systems, and regulations governing hydrogen infrastructure and applications.

REFERENCES

1 International Energy Forum, “Scaling Up: Three Low-Carbon Hydrogen Plants Leading the Charge,” September 21, 2022, https://www.ief.org/news/scaling-up-three-low-carbon-hydrogen-plants-leading-the-charge#:~:text=Our%20latest%20hydrogen%20market%20report%20finds%20low%2Dcarbon,hydrogen%20production%2C%20in%20pursuit%20of%20commercial%20viability.

2 Mason Hamilton et al., *Hydrogen Market Pathways Scaling-Up the Hydrogen Market*, International Energy Forum, June 2022, https://www.ief.org/programs/hydrogen-market-pathways#report.

3 Ekona, “Ekona Power Inc. Pilots Methane Pyrolysis Solution for low-cost Clean Hydrogen,” January 3, 2024, https://ekonapower.com/ekona-power-inc-pilots-methane-pyrolysis-solution-for-low-cost-clean-hydrogen/.

4 K. Ramirez et al., “Hydrogen Reality Check: Distilling Green Hydrogen’s Water Consumption,” https://rmi.org/hydrogen-reality-check-distilling-green-hydrogens-water-consumption/.

5 Ministry of Trade and Industry Singapore, *Singapore’s National Hydrogen Strategy*, https://www.mti.gov.sg/Industries/Hydrogen.

6 International Energy Agency (IEA), “Hydrogen Industry Development Plan (2021-2035),” January 13, 2023, https://www.iea.org/policies/16977-hydrogen-industry-development-plan-2021-2035.

7 “Summary for Policymakers,” Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II, and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Geneva, Switzerland: Intergovernmental Panel on Climate Change) (IPCC), 2023, https://www.ipcc.ch/report/sixth-assessment-report-cycle/.

8 IPCC, “Climate Change 2022: Mitigation of Climate Change,” Sixth Assessment Report, 2022, https://www.ipcc.ch/report/ar6/wg3/.

9 Ian Shine, “Spending on low-carbon energy technology is on the brink of overtaking fossil fuels. These 4 charts tell the full story,” World Economic Forum, 2023, accessed February 5, 2024, https://www.weforum.org/agenda/2023/02/low-carbon-investment-record-2022/.

10 Ian Shine, “Spending on low-carbon energy technology is on the brink of overtaking fossil fuels. These 4 charts tell the full story, “World Economic Forum, 2003, accessed February 5, 2024, https://www.weforum.org/agenda/2023/02/low-carbon-investment-record-2022/.

11 Ian Shine, “Spending on low-carbon energy technology is on the brink of overtaking fossil fuels. These 4 charts tell the full story, “World Economic Forum, 2003, accessed February 5, 2024, https://www.weforum.org/agenda/2023/02/low-carbon-investment-record-2022/.

12 IEA, *World Energy Outlook 2023*, December 2023, https://www.iea.org/reports/world-energy-outlook-2023.

13 Ian Shine, “Spending on low-carbon energy technology is on the brink of overtaking fossil fuels. These 4 charts tell the full story, “World Economic Forum, 2003, accessed February 5, 2024, https://www.weforum.org/agenda/2023/02/low-carbon-investment-record-2022/.

14 Hydrogen Council and McKinsey & Company, *Hydrogen for Net-Zero*, November 2021, p. 13, https://hydrogencouncil.com/wp-content/uploads/2021/11/Hydrogen-for-Net-Zero.pdf.

15 Johannes Truby et al., “Green Hydrogen: Energizing the Path to Net Zero,” Deloitte, June 19, 2023, https://www.deloitte.com/global/en/issues/climate/green-hydrogen.html.

16 Anmar Frangoul, “Hydrogen Generation Could Become a $1 Trillion per Year Market, Goldman Sachs Says,” CNBC, February 23, 2022, https://www.cnbc.com/2022/02/23/hydrogen-generation-could-become-1-trillion-market-goldman-sachs.html.

17 Energy Futures Initiative (EFI), “The U.S. Hydrogen Demand Action Plan,” EFI Foundation, February 9, 2023, https://efifoundation.org/reports/the-u-s-hydrogen-demand-action-plan-2/.

18 Hydrogen Council and McKinsey & Company, *Global Hydrogen Flows: Hydrogen Trade as a Key Enabler for Efficient Decarbonization*, October 5, 2022, p. 16, https://hydrogencouncil.com/en/global-hydrogen-flows/.

19 Polly Martin, “Japanese Oil Giant Buys Stake in US Hydrogen Producer with Export Ambitions,” *Hydrogen Insight*, January 12, 2024, https://www.hydrogeninsight.com/production/japanese-oil-giant-buys-stake-in-us-hydrogen-producer-with-export-ambitions/2-1-1582292.

20 IEA, *World Energy Outlook 2023*, December 2023, p. 105, https://www.iea.org/reports/world-energy-outlook-2023.

21 IEA, *Global Hydrogen Review 2023*, September 2023, p. 64, https://www.iea.org/reports/global-hydrogen-review-2023.

22 W. Almazeedi et al., *The Clean Hydrogen Economy and Saudi Arabia. Domestic Developments and International Opportunities*, May 2024, https://www.routledge.com/The-Clean-Hydrogen-Economy-and-Saudi-Arabia-Domestic-Developments-and-International-Opportunities/Shabaneh-Roychoudhury-Braun-Saxena/p/book/9781032278315.

23 Mitsubishi Heavy Industries Group, The Color Wheel, https://spectra.mhi.com/the-colors-of-hydrogen-expanding-ways-of-decarbonization.

24 The U.S. Department of Energy, "Hydrogen Production. Hydrogen and Fuel Cell Technologies Office," https://www.energy.gov/eere/fuelcells/hydrogen-production.

25 IEA, *Global Hydrogen Review 2023*, September 2023, p. 23, https://www.iea.org/reports/global-hydrogen-review-2023.

26 IEA, *Global Hydrogen Review 2023*, September 2023, p. 22, https://www.iea.org/reports/global-hydrogen-review-2023.

27 IEA, *Global Hydrogen Review 2023*, September 2023, p. 25, https://www.iea.org/reports/global-hydrogen-review-2023.

28 IEA, *Global Hydrogen Review 2023*, September 2023, p. 21, https://www.iea.org/reports/global-hydrogen-review-2023.

29 IEA, *Global Hydrogen Review 2023*, September 2023, p. 21, https://www.iea.org/reports/global-hydrogen-review-2023.

30 T. Wood et al., "Hydrogen: hype, hope, or hard work?" Grattan Institute. 2023.

31 Hydrogen Council and McKinsey & Company, *Hydrogen Insights 2024*, September 2024, pp. 4 and 20, https://hydrogencouncil.com/wp-content/uploads/2024/09/Hydrogen-Insights-2024.pdf.

32 Joanna Sampson, "Hydrogen Insights 2023 December Update," Hydrogen Council, December 12, 2023, p. 13, https://hydrogencouncil.com/en/hydrogen-insights-2023-december-update/.

33 Dolf Gielen et. al., "Unleashing the power of hydrogen for the clean energy transition," World Bank Blogs, https://blogs.worldbank.org/en/energy/unleashing-power-hydrogen-clean-energy-transition#:~:text=Moreover%2C%20total%20hydrogen%20demand%20needs,fold%20between%20now%20and%202030.&text=Green%20hydrogen%20is%20currently%20considerably,hydrogen%E2%80%94produ.

34 Dolf Gielen et al., "Unleashing the power of hydrogen for the clean energy transition," World Bank Blogs, 2023, accessed February 6, 2024, https://blogs.worldbank.org/energy/unleashing-power-hydrogen-clean-energy-transition.

35 IEA, *Global Hydrogen Review 2023*, September 2023, p. 148, https://www.iea.org/reports/global-hydrogen-review-2023.

36 IEA, *Global Hydrogen Review 2023*, September 2023, p. 162, https://www.iea.org/reports/global-hydrogen-review-2023.

37 IEA, *Global Hydrogen Review 2023*, September 2023, p. 163, https://www.iea.org/reports/global-hydrogen-review-2023.

38 IEA, *Global Hydrogen Review 2023*, September 2023, p. 164, https://www.iea.org/reports/global-hydrogen-review-2023.

39 Energy Futures Initiative (EFI) and King Abdullah Petroleum Studies and Research Center (KAPSARC), *A Global Hydrogen Future - Workshop Report*, March 2023, https://energyfuturesinitiative.org/wp-content/uploads/sites/2/2023/03/A-Global-Hydrogen-Future-Workshop-Report_FINAL_3-6-2023-2.pdf.

40 EFI and KAPSARC, *A Global Hydrogen Future - Workshop Report*, March 2023, https://energyfuturesinitiative.org/wp-content/uploads/sites/2/2023/03/A-Global-Hydrogen-Future-Workshop-Report_FINAL_3-6-2023-2.pdf.

41 Hydrogen Council and McKinsey & Company, *Global Hydrogen Flows: Hydrogen Trade as a Key Enabler for Efficient Decarbonization*, October 5, 2022, p. 12, https://hydrogencouncil.com/en/global-hydrogen-flows/.

42 Hydrogen Council and McKinsey & Company, *Global Hydrogen Flows: Hydrogen Trade as a Key Enabler for Efficient Decarbonization*, October 5, 2022, p. 13, https://hydrogencouncil.com/en/global-hydrogen-flows/.

43 Hydrogen Council and McKinsey & Company, *Global Hydrogen Flows: Hydrogen Trade as a Key Enabler for Efficient Decarbonization*, October 5, 2022, p. 35, https://hydrogencouncil.com/en/global-hydrogen-flows/.

44 Joanna Sampson, "Hydrogen Insights 2023 December Update," Hydrogen Council, December 12, 2023, p. 14, https://hydrogencouncil.com/en/hydrogen-insights-2023-december-update/.

45 IEA, "Hydrogen," accessed February 15, 2024, https://www.iea.org/energy-system/low-emission-fuels/hydrogen.

46 EHB European Hydrogen Backbone, "The European Hydrogen Backbone (EHB) Initiative," accessed February 23, 2024, https://ehb.eu/.

47 Marek Vočadlo, "European Commission Gave CEHC PCI Status," Central European Hydrogen Corridor, December 11, 2023, https://www.cehc.eu/european-commission-gave-cehc-pci-status/.

48 IEA, *Global Hydrogen Review 2023*, September 2023, p. 112, https://www.iea.org/reports/global-hydrogen-review-2023.

49 International Renewable Energy Agency (IRENA), *Accelerating Hydrogen Deployment in the G7: Recommendations for the Hydrogen Action Pact*, November 16, 2022, https://www.irena.org/Publications/2022/Nov/Accelerating-hydrogen-deployment-in-the-G7.

50 IRENA and World Trade Organization (WTO), "International Trade and Green Hydrogen: Supporting the Global Transition to a Low-Carbon Economy," December 2023, p. 14, https://www.irena.org/Publications/2023/Dec/International-trade-and-green-hydrogen-Supporting-the-global-transition-to-a-low-carbon-economy.

51 IEA, “Hydrogen,” accessed February 15, 2024, https://www.iea.org/energy-system/low-emission-fuels/hydrogen.

52 Anne-Sophie Corbeau and Rio Pramudita Kaswiyanto, “What do national hydrogen strategies tell us about potential Future Trade?” Center on Global Energy Policy at Columbia SIPA, May 2, 2024, https://www.energypolicy.columbia.edu/what-do-national-hydrogen-strategies-tell-us-about-potential-future-trade/.

53 Michael Liebreich, “The Clean Hydrogen Ladder: an introduction, August 14, 2021, https://drive.google.com/file/d/1lK0dOHxq-sjpELrJ5hWIGX-66dCy_vWCW/view.

54 IEA, “Hydrogen,” accessed February 7, 2024, https://www.iea.org/energy-system/low-emission-fuels/hydrogen.

55 IEA, *World Energy Outlook 2023*, December 2023, p. 293, https://www.iea.org/reports/world-energy-outlook-2023.

56 IEA, *Global Hydrogen Review 2023*, September 2023, p. 47, https://www.iea.org/reports/global-hydrogen-review-2023.

57 Jeffrey Rissman, *Zero-Carbon Industry: Transformative Technologies and Policies to Achieve Sustainable Prosperity*, Columbia University Press, 2024.

58 IEA, *Global Hydrogen Review 2023*, September 2023, p. 22, https://www.iea.org/reports/global-hydrogen-review-2023.

59 Sushant Gupta, “From Grey and Brown to Green and Blue: Low-Carbon Hydrogen in Refining,” Wood Mackenzie, June 9, 2022, https://www.woodmac.com/news/opinion/from-grey-and-brown-to-green-and-blue-low-carbon-hydrogen-in-refining/.

60 Sushant Gupta, “From Grey and Brown to Green and Blue: Low-Carbon Hydrogen in Refining,” Wood Mackenzie, June 9, 2022, https://www.woodmac.com/news/opinion/from-grey-and-brown-to-green-and-blue-low-carbon-hydrogen-in-refining/.

61 IEA, “Opportunities for Hydrogen Production with CCUS in China,” 2022, p. 13, https://www.iea.org/reports/opportunities-for-hydrogen-production-with-ccus-in-china/executive-summary.

62 BloombergNEF and Climate Technology Coalition, *Scaling Up Hydrogen: The Case for Low-Carbon Ammonia*, January 11, 2024, p. 5 https://assets.bbhub.io/professional/sites/24/CTC-whitepaper_Ammonia_Final.pdf.

63 IEA “Ammonia Technology Roadmap: Towards More Sustainable Nitrogen Fertiliser Production,” October 2021, https://www.iea.org/reports/ammonia-technology-roadmap.

64 Peter Aagaard et al., “From Green Ammonia to Lower-Carbon Foods,” McKinsey & Company, December 11, 2023, https://www.mckinsey.com/industries/agriculture/our-insights/from-green-ammonia-to-lower-carbon-foods.

65 BloombergNEF and Climate Technology Coalition, *Scaling Up Hydrogen: The Case for Low-Carbon Ammonia*, January 11, 2024, p. 8, https://assets.bbhub.io/professional/sites/24/CTC-whitepaper_Ammonia_Final.pdf.

66 David Sandalow et al., “Low-Carbon Ammonia Roadmap,” Innovation for Cool Earth Forum, November 2022, p. 2, https://www.icef.go.jp/pdf/summary/roadmap/icef2022_roadmap_Low-Carbon_Ammonia.pdf

67 BloombergNEF and Climate Technology Coalition, *Scaling Up Hydrogen: The Case for Low-Carbon Ammonia*, January 11, 2024, p. 6, https://assets.bbhub.io/professional/sites/24/CTC-whitepaper_Ammonia_Final.pdf.

68 BloombergNEF and Climate Technology Coalition, *Scaling Up Hydrogen: The Case for Low-Carbon Ammonia*, January 11, 2024, p. 6, https://assets.bbhub.io/professional/sites/24/CTC-whitepaper_Ammonia_Final.pdf.

69 David Sandalow et al., “Low-Carbon Ammonia Roadmap,” Innovation for Cool Earth Forum, November 2022, p. 12, https://www.icef.go.jp/pdf/summary/roadmap/icef2022_roadmap_Low-Carbon_Ammonia.pdf.

70 BloombergNEF and Climate Technology Coalition, *Scaling Up Hydrogen: The Case for Low-Carbon Ammonia*, January 11, 2024, p. 6, https://assets.bbhub.io/professional/sites/24/CTC-whitepaper_Ammonia_Final.pdf.

71 David Sandalow et al., “Low-Carbon Ammonia Roadmap,” Innovation for Cool Earth Forum, November 2022, p. 2, https://www.icef.go.jp/pdf/summary/roadmap/icef2022_roadmap_Low-Carbon_Ammonia.pdf.

72 BloombergNEF and Climate Technology Coalition, *Scaling Up Hydrogen: The Case for Low-Carbon Ammonia*, January 11, 2024, p. 6, https://assets.bbhub.io/professional/sites/24/CTC-whitepaper_Ammonia_Final.pdf.

73 BloombergNEF and Climate Technology Coalition, *Scaling Up Hydrogen: The Case for Low-Carbon Ammonia*, January 11, 2024, https://assets.bbhub.io/professional/sites/24/CTC-whitepaper_Ammonia_Final.pdf.

74 BloombergNEF and Climate Technology Coalition, *Scaling Up Hydrogen: The Case for Low-Carbon Ammonia*, January 11, 2024, p. 9, https://assets.bbhub.io/professional/sites/24/CTC-whitepaper_Ammonia_Final.pdf.

75 IRENA and WTO, *International Trade and Green Hydrogen: Supporting the Global Transition to a Low-Carbon Economy*, December 2023, p. 20, https://www.irena.org/Publications/2023/Dec/International-trade-and-green-hydrogen-Supporting-the-global-transition-to-a-low-carbon-economy.

76 IRENA and WTO, *International Trade and Green Hydrogen: Supporting the Global Transition to a Low-Carbon Economy*, December 2023, p. 22, https://www.irena.org/Publications/2023/Dec/International-trade-and-green-hydrogen-Supporting-the-global-transition-to-a-low-carbon-economy.

77 IRENA and WTO, *Innovation Outlook: Renewable Ammonia*, 2022, p. 28, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf?rev=50e91f792d3442279fca0d4ee24757ea.

78 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.

79 Air Products, "NEOM Green Hydrogen Complex," accessed February 23, 2024, https://www.airproducts.com/energy-transition/neom-green-hydrogen-complex.

80 NEOM, "About Us: A Vision of What a New Future Might Look Like," accessed February 23, 2024, https://www.neom.com/en-us/about.

81 IRENA and Ammonia Energy Association, "Innovation Outlook: Renewable Ammonia," 2022, p. 29, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf?rev=50e91f792d3442279fca0d4ee24757ea.

82 American Chemical Society, "ACS Publications: Industrial & Engineering Chemistry Research," accessed July 8, 2024, https://pubs.acs.org/doi/10.1021/acs.iecr.3c01419#.

83 International Renewable Energy Agency (IRENA) and Ammonia Energy Association, *Innovation Outlook: Renewable Ammonia*, 2022, p. 78, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/May/IRENA_Innovation_Outlook_Ammonia_2022.pdf?rev=50e91f792d3442279fca0d4ee24757ea.

84 IRENA and Methanol Institute, *Innovation Outlook: Renewable Methanol*, 2021, p. 12, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf.

85 "Methanol Price and Supply/Demand," Methanol Institute (blog), accessed February 9, 2024, https://www.methanol.org/methanol-price-supply-demand/.

86 IRENA and Methanol Institute, *Innovation Outlook: Renewable Methanol*, 2021, p. 23, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf.

87 IRENA and Methanol Institute, *Innovation Outlook: Renewable Methano*l, 2021, p. 23, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf.

88 "Methanol," Methanol Market Services Asia, accessed February 9, 2024, https://www.methanolmsa.com/value-chain/methanol/.

89 IRENA and Methanol Institute, *Innovation Outlook: Renewable Methanol*, 2021, p. 23, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf.

90 Felix Schorn et al., "Methanol as a Renewable Energy Carrier: An Assessment of Production and Transportation Costs for Selected Global Locations," *Advances in Applied Energy 3* (August 25, 2021): 100050, https://doi.org/10.1016/j.adapen.2021.100050.

91 IRENA and Methanol Institute, *Innovation Outlook: Renewable Methanol*, 2021, p. 70, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf.

92 IRENA and Methanol Institute, *Innovation Outlook: Renewable Methanol*, 2021, p. 76, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf.

93 IRENA and WTO, *International Trade and Green Hydrogen: Supporting the Global Transition to a Low-Carbon Economy*, December 2023, p. 14, https://www.irena.org/Publications/2023/Dec/International-trade-and-green-hydrogen-Supporting-the-global-transition-to-a-low-carbon-economy.

94 Hydrogen Council and McKinsey & Company, *Global Hydrogen Flows: Hydrogen Trade as a Key Enabler for Efficient Decarbonization*, October 5, 2022, p. 20, https://hydrogencouncil.com/en/global-hydrogen-flows/.

95 "Cutting the Carbon Intensity of Steel Using Hydrogen and Renewables," International Energy Forum, January 23, 2024, https://www.ief.org/news/cutting-the-carbon-intensity-of-steel-using-hydrogen-and-renewables.

96 World Steel Association, "World Steel in Figures 2023," May 2023, https://worldsteel.org/steel-topics/statistics/world-steel-in-figures-2023/.

97 Energy Futures Initiative (EFI), *The Future of Clean Hydrogen in the United States*, EFI Foundation, September 1, 2021, p. 53, https://efifoundation.org/reports/the-future-of-clean-hydrogen-in-the-united-states/.

98 Christian Hoffmann et. al., *Decarbonization Challenge for Steel: Hydrogen as a Solution in Europe*, McKinsey & Company, April 2020, https://www.mckinsey.com/~/media/McKinsey/Industries/Metals%20and%20Mining/Our%20Insights/Decarbonization%20challenge%20for%20steel/Decarbonization-challenge-for-steel.pdf.

99 Josué Rodríguez Diez et al., "Decarbonization Pathways, Strategies, and Use Cases to Achieve Net-Zero CO_2 Emissions in the Steelmaking Industry," *Energies* 16, no. 21 (January 2023): 7360, https://doi.org/10.3390/en16217360.

100 World Steel Association, "World Steel in Figures 2023," May 2023, https://worldsteel.org/steel-topics/statistics/world-steel-in-figures-2023/.

101 World Steel Association, "World Steel in Figures 2023," May 2023, https://worldsteel.org/steel-topics/statistics/world-steel-in-figures-2023/.

102 EFI Foundation, *Hydrogen Market Formation: An Evaluation Framework*, January 2024, p. 67, https://efifoundation.org/wp-content/uploads/sites/3/2024/01/H2-Market-Evaluation-FINAL-with-cover.pdf.

103 Messe Dusseldort GmbH, "Decarbonization Project 'tkH2Steel' by Thyssenkrupp Steel Supported by Federal and State Governments," GIFA, accessed February 22, 2024, https://www.gifa.com/en/Media_News/News/Decarbonization_project_tkH2Steel_by_thyssenkrupp_Steel_supported_by_federal_and_state_governments.

104 Agamoni Ghosh, "China's Decarbonization Goals Get Boost from Baowu's Carbon Reduction Plans," S&P Global Commodity Insights, December 3, 2021, https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/120321-chinas-decarbonization-goals-get-boost-from-baowus-carbon-reduction-plans.

105 IEA, "Iron and Steel Technology Roadmap," IEA, Paris, 2020, https://www.iea.org/reports/iron-and-steel-technology-roadmap, License: CC BY 4.0

106 Joanna Sampson, *Hydrogen Insights 2023 December Update*, Hydrogen Council, December 12, 2023, p. 12, https://hydrogencouncil.com/en/hydrogen-insights-2023-december-update/.

107 International Maritime Organization (IMO), "Initial IMO GHG Strategy," accessed February 16, 2024, https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx.

108 IRENA and Methanol Institute, *Innovation Outlook: Renewable Methanol*, 2021, p. 28, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf.

109 Joanna Sampson, *Hydrogen Insights 2023 December Update*, Hydrogen Council, December 12, 2023, p. 14, https://hydrogencouncil.com/en/hydrogen-insights-2023-december-update/.

110 Global Maritime Forum and Getting to Zero Coalition, *Mapping of Zero-Emission Pilots and Demonstration Projects*, May 2023, https://www.globalmaritimeforum.org/content/2023/05/Getting-to-Zero-Coalition_Mapping-of-Zero-Emission-Pilots-and-Demonstration-Projects_Fourth-edition.pdf.

111 David Sandalow et al., "Low-Carbon Ammonia Roadmap," Innovation for Cool Earth Forum, November 2022, p. 50, https://www.icef.go.jp/pdf/summary/roadmap/icef2022_roadmap_Low-Carbon_Ammonia.pdf.

112 King Abdullah Petroleum Studies and Research Center (KAPSARC) and Energy Futures Initiative (EFI), "Powering the Future of Aviation: Exploring the Role of Hydrogen and Power-to- Liquid in Sustainable Aviation Fuels," November 30, 2023, p. 3, https://www.kapsarc.org/research/publications/powering-the-future-of-aviation-exploring-the-role-of-hydrogen-and-power-to-liquid-in-sustainable-aviation-fuels/.

113 KAPSARC and EFI, "Powering the Future of Aviation: Exploring the Role of Hydrogen and Power-to- Liquid in Sustainable Aviation Fuels," November 30, 2023, p. 8, https://www.kapsarc.org/research/publications/powering-the-future-of-aviation-exploring-the-role-of-hydrogen-and-power-to-liquid-in-sustainable-aviation-fuels/.

114 KAPSARC and EFI, "Powering the Future of Aviation: Exploring the Role of Hydrogen and Power-to- Liquid in Sustainable Aviation Fuels," November 30, 2023, p. 13, https://www.kapsarc.org/research/publications/powering-the-future-of-aviation-exploring-the-role-of-hydrogen-and-power-to-liquid-in-sustainable-aviation-fuels/.

115 Joanna Sampson, *Hydrogen Insights 2023 December Update*, Hydrogen Council, December 12, 2023, p. 17, https://hydrogencouncil.com/en/hydrogen-insights-2023-december-update/.

116 IEA, "Japan 2021: Energy Policy Review," May 2021, https://www.iea.org/countries/japan.

117 Jane Nakano, "Japan's Hydrogen Industrial Strategy," October 21, 2021, https://www.csis.org/analysis/japans-hydrogen-industrial-strategy.

118 Liu Pingkuo and Han Xue, "Comparative Analysis on Similarities and Differences of Hydrogen Energy Development in the World's Top 4 Largest Economies: A Novel Framework," *International Journal of Hydrogen Energy* 47, no. 16 (February 22, 2022): 9485–9503, https://doi.org/10.1016/j.ijhydene.2022.01.038.

119 "Global Hydrogen Station Deployments Surpass 1,000; China Leads," Green Car Congress, January 15, 2023, https://www.greencarcongress.com/2023/01/20230115-h2.html.

120 Government of Japan, Public Relations Office, "Highlighting Japan February 2015," https://www.gov-online.go.jp/eng/publicity/book/hlj/html/201502/201502_05_en.html.

121 Government of Japan, "Kansai International Airport's Cutting-Edge Hydrogen Experiment," Public Relations Office, February 2015, https://www.gov-online.go.jp/eng/publicity/book/hlj/html/201502/201502_05_en.html.

122 Airbus, Press Release, June 10, 2022, https://www.airbus.com/en/newsroom/press-releases/2022-06-airbus-and-kansai-airports-partner-to-study-the-use-of-hydrogen-in.

123 Sonal Patel, "Fukushima Hydrogen Energy Research Field Demonstrates Hydrogen Integration," *Power Magazine*, July 1, 2022, https://www.powermag.com/fukushima-hydrogen-energy-research-field-demonstrates-hydrogen-integration/.

124 IRENA, *Accelerating Hydrogen Deployment in the G7: Recommendations for the Hydrogen Action Pact*, November 16, 2022, https://www.irena.org/Publications/2022/Nov/Accelerating-hydrogen-deployment-in-the-G7.

125 CSIRO, *Hydrogen R&D Collaboration Opportunities: Japan*, Australia's National Science Agency, August 18, 2022, https://explore.mission-innovation.net/wp-content/uploads/2023/04/H2RDD-Japan-FINAL.pdf.

126 Hydrogen Utilization Study Group in Chubu, "Summary of Activities for Hydrogen Utilization in Chubu in 2030," Air Liquide, February 19, 2021, https://jp.airliquide.com/sites/al_jp/files/2022-09/20210219_summary_of_activities_for_h2_in_chubu_en.pdf.

127 CSIRO, *Hydrogen R&D Collaboration Opportunities: Japan*, Australia's National Science Agency, August 18, 2022, p. 31, https://explore.mission-innovation.net/wp-content/uploads/2023/04/H2RDD-Japan-FINAL.pdf.

128 Hiroki Yoshida, "Japan's Vision and Action toward Hydrogen Economy," Ministry of Economy, Trade and Industry (METI), Japan, May 2022, https://eu-japan.eu/sites/default/files/imce/METI%20Hiroki%20Yoshida%202022.5.25.pdf.

129 HESC, "Japan commits QAUD$2.1 billion to establish world's first liquefied hydrogen supply chain," March 7, 2023, https://www.hydrogenenergysupplychain.com/japan-commits-aud2-35-billion-to-establish-liquefied-hydrogen-supply-chain/.

130 Joanna Sampson, *Hydrogen Insights 2023 December Update*, Hydrogen Council, December 12, 2023, p. 14, https://hydrogencouncil.com/en/hydrogen-insights-2023-december-update/.

131 IEA, *Global Hydrogen Review 2023*, September 2023, p. 42, https://www.iea.org/reports/global-hydrogen-review-2023.

132 IEA, *Global Hydrogen Review 2023*, September 2023, p. 42, https://www.iea.org/reports/global-hydrogen-review-2023.

133 The Royal Society, "Large-Scale Electricity Storage," September 2023, p. 38, https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/large-scale-electricity-storage/.

134 Tom DiChristopher, "Hydrogen Technology Faces Efficiency Disadvantage in Power Storage Race," S&P Global Market Intelligence, June 24, 2021, https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/hydrogen-technology-faces-efficiency-disadvantage-in-power-storage-race-65162028.

135 IRENA, "Innovation Can Pave the Way to Decarbonise High-Temperature Heat in Industries," International Renewable Energy Agency, September 13, 2023, https://www.irena.org/News/articles/2023/Sep/Innovation-can-pave-the-way-to-decarbonise-high-temperature-heat-in-industries.

136 Julio Friedmann et al., "Low-Carbon Heat Solutions for Heavy Industry: Sources, Options, and Costs Today," Center on Global Energy Policy at Columbia University SIPA, October 7, 2019, p. 45, https://www.energypolicy.columbia.edu/publications/low-carbon-heat-solutions-heavy-industry-sources-options-and-costs-today/.

137 Julio Friedmann et al., "Low-Carbon Heat Solutions for Heavy Industry: Sources, Options, and Costs Today," Center on Global Energy Policy at Columbia University SIPA, October 7, 2019, p. 46, https://www.energypolicy.columbia.edu/publications/low-carbon-heat-solutions-heavy-industry-sources-options-and-costs-today/.

138 Christoph Beumelburg, "Key Contribution to Heidelberg Cement's Ambitious New Sustainability Targets: CCUS Project in Sweden Takes next Step," Heidelberg Materials, May 30, 2022, https://www.heidelbergmaterials.com/en/pr-30-05-2022.

139 M. Zier et al., "A review of decarbonization options for the glass industry," *Energy Conversion and Management* (2021): X, 10, 100083.

140 EFI, *The U.S. Hydrogen Demand Action Plan*, EFI Foundation, February 9, 2023, p. 60, https://efifoundation.org/reports/the-u-s-hydrogen-demand-action-plan-2/.

141 Konstantinos Kanellopoulos et al., "Blending Hydrogen from Electrolysis into the European Gas Grid," European Commission, January 14, 2022, p. 5, https://doi.org/10.2760/908387.

142 IRENA, *Water for Hydrogen Production*, December 10, 2023, p. 6, https://www.irena.org/Publications/2023/Dec/Water-for-hydrogen-production.

143 IRENA, *Water for Hydrogen Production*, December 10, 2023, p. 8, https://www.irena.org/Publications/2023/Dec/Water-for-hydrogen-production.

144 Kaitlyn Ramirez et al., "Hydrogen Reality Check: Distilling Green Hydrogen's Water Consumption," RMI, August 2, 2023, https://rmi.org/hydrogen-reality-check-distilling-green-hydrogens-water-consumption/.

145 David Tonelli et al., "Global Land and Water Limits to Electrolytic Hydrogen Production Using Wind and Solar Resources," *Nature Communications* 14, no. 1 (September 8, 2023): 5532, https://doi.org/10.1038/s41467-023-41107-x.

146 Kaitlyn Ramirez et al., "Hydrogen Reality Check: Distilling Green Hydrogen's Water Consumption," RMI, August 2, 2023, https://rmi.org/hydrogen-reality-check-distilling-green-hydrogens-water-consumption/.

147 Robert F. Service, “Splitting seawater could provide an endless source of green hydrogen,” Science.org, March 15, 2023, https://www.science.org/content/article/splitting-seawater-provide-endless-source-green-hydrogen#:~:text=The%20membranes%20that%20screen%20out%20the%20salt%20resemble,about%20%240.01%20per%20kilogram%20to%20green%20hydrogen%E2%80%99s%20cost.

148 Kaitlyn Ramirez et al., “Hydrogen Reality Check: Distilling Green Hydrogen’s Water Consumption,” RMI, August 2, 2023, https://rmi.org/hydrogen-reality-check-distilling-green-hydrogens-water-consumption/.

149 Taken from a PPT presentation during the Global Hydrogen Future MENA Workshop, Christopher Hebling, Hydrogen Technologies, Fraunhofer ISE, Moderated Panel discussion on MENA Supply, Demand, and Strategies, November 27, 2023.

150 IEA, *Global Hydrogen Review 2023*, September 2023, p. 148, https://www.iea.org/reports/global-hydrogen-review-2023.

151 IEA, *Global Hydrogen Review 2023*, September 2023, p. 149, https://www.iea.org/reports/global-hydrogen-review-2023.

152 Center on Global Energy Policy (CGEP), “National Hydrogen Strategies and Roadmap Tracker,” February 1, 2024, https://www.energypolicy.columbia.edu/publications/national-hydrogen-strategies-and-roadmap-tracker/.

153 Financial Times, Kawasaki Heavy Industries and Hydrogen Council content, https://www.ft.com/partnercontent/kawasaki-heavy-industries/what-is-needed-for-hydrogen-to-really-take-off.html?utm_source=FT&utm_medium=Premium_Native_Amplification&utm_content=ft_marketing.

154 European Council, “Fit for 55,” December 13, 2023, https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/.

155 European Council, “Council and Parliament Reach Provisional Deal on Renewable Energy Directive,” March 30, 2023, https://www.consilium.europa.eu/en/press/press-releases/2023/03/30/council-and-parliament-reach-provisional-deal-on-renewable-energy-directive/.

156 European Parliament and Council of the European Union, "REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the Use of Renewable and Low-Carbon Fuels in Maritime Transport, and Amending Directive 2009/16/EC," 2023, https://data.consilium.europa.eu/doc/document/PE-26-2023-INIT/en/pdf.

157 IEA, *Global Hydrogen Review 2023*, September 2023, p. 150, https://www.iea.org/reports/global-hydrogen-review-2023.

158 European Council, “Internal Markets in Renewable and Natural Gases and in Hydrogen: Council and Parliament Reach Deal,” November 28, 2023, https://www.consilium.europa.eu/en/press/press-releases/2023/11/28/internal-markets-in-renewable-and-natural-gases-and-in-hydrogen-council-and-parliament-reach-deal/.

159 “Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the Internal Markets for Renewable and Natural Gases and for Hydrogen (Recast),” 2021, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2021%3A804%3AFIN&qid=1640001545187.

160 Stefan Krumpelmann, “Romania Slashes Renewable Hydrogen Targets | Latest Market News,” November 9, 2023, https://www.argusmedia.com/en/news-and-insights/latest-market-news/2507745-romania-slashes-renewable-hydrogen-targets.

161 IEA, *Global Hydrogen Review 2023*, September 2023, p. 152, https://www.iea.org/reports/global-hydrogen-review-2023.

162 Vipul Garg and Donavan Lim, “Clear Guidelines, Formation of CfD Schemes Likely to Unlock Asian Hydrogen Market in 2024,” December 29, 2023, https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/122923-clear-guidelines-formation-of-cfd-schemes-likely-to-unlock-asian-hydrogen-market-in-2024.

163 Vipul Garg and Donavan Lim, “Clear Guidelines, Formation of CfD Schemes Likely to Unlock Asian Hydrogen Market in 2024,” December 29, 2023, https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/122923-clear-guidelines-formation-of-cfd-schemes-likely-to-unlock-asian-hydrogen-market-in-2024.

164 Leigh Collins, “Japan to provide 15-year subsidies for locally produced and imported hydrogen after parliament passes H2 law,” Hydrogeninsight, May 17, 2024, https://www.hydrogeninsight.com/policy/japan-to-provide-15-year-subsidies-for-locally-produced-and-imported-hydrogen-after-parliament-passes-h2-law/2-1-1646040.

165 Vipul Garg and Donavan Lim, “Clear Guidelines, Formation of CfD Schemes Likely to Unlock Asian Hydrogen Market in 2024,” December 29, 2023, https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/122923-clear-guidelines-formation-of-cfd-schemes-likely-to-unlock-asian-hydrogen-market-in-2024.

166 Arnes Biogradlija, “Chile Awards Six New Green Hydrogen Projects,” *H2 Energy News* (blog), January 21, 2022, https://energynews.biz/chile-awards-six-new-green-hydrogen-projects/.

167 Jyoti Gulia et al., “India’s $2.1bn Leap towards Its Green Hydrogen Vision,” Institute for Energy Economics and Financial Analysis, March 7, 2024, https://ieefa.org/resources/indias-21bn-leap-towards-its-green-hydrogen-vision.

168 PTI, “Govt Likely to Come out with a Mandate on Green Hydrogen Usage: MNRE Secretary,” ETEnergyworld.com, July 8, 2023, https://energy.economictimes.indiatimes.com/news/renewable/govt-likely-to-come-out-with-a-mandate-on-green-hydrogen-usage-mnre-secretary/101586872.

169 Department of Climate Change, Energy, the Environment and Water, “Funding Available for Clean Hydrogen Industrial Hubs,” Australian Government, September 22, 2021, https://www.dcceew.gov.au/about/news/funding-available-for-clean-hydrogen-industrial-hubs.

170 Clean Energy Finance Corporation, "CEFC Hydrogen Investment Fuels World's Heaviest Fuel Cell Electric Trucks," November 8, 2021, https://www.cefc.com.au/media/media-release/cefc-hydrogen-investment-fuels-world-s-heaviest-fuel-cell-electric-trucks/.

171 Australian Renewable Energy Agency, "Hydrogen Headstart," accessed March 7, 2024, https://arena.gov.au/funding/hydrogen-headstart/.

172 Department for Energy Security and Net Zero, Claire Coutinho and Lord Callanan, "Boost for UK Hydrogen as government backs world-leading industry," UK Government Press Release, February 27, 2024, https://www.gov.uk/government/news/boost-for-uk-hydrogen-as-government-backs-world-leading-industry.

173 Ministry of Mines and Energy Namibia, *Namibia Green Hydrogen and Derivatives Strategy*, November 2022, https://www.ensafrica.com/uploads/newsarticles/0_namibia-gh2-strategy-rev2.pdf.

174 The World Bank, "World Bank Proposes 10 GW Clean Hydrogen Initiative to Boost Adoption of Low-Carbon Energy," November 17, 2023, https://www.worldbank.org/en/news/press-release/2023/11/17/world-bank-proposes-10-gw-clean-hydrogen-initiative-to-boost-adoption-of-low-carbon-energy#:~:text=WASHINGTON%2C%20Nov.,energy%20access%20in%20developing%20countries.

175 Energy Sector Management Assistance Program (ESMAP), Organisation for Economic Co-operation and Development (OECD), Global Infrastructure Facility, and Hydrogen Council, *Scaling Hydrogen Financing for Development*. ESMAP, Washington, DC: World Bank 2023, License: Creative Commons Attribution CC BY 3.0 IGO, https://openknowledge.worldbank.org/server/api/core/bitstreams/1624d96d-4ad0-4584-82c8-7b106a76555a/content.

176 IEA, *Opportunities for Hydrogen Production with CCUS in China*, https://www.iea.org/reports/opportunities-for-hydrogen-production-with-ccus-in-china/executive-summary.

177 Australian Ministry for Industry, Energy and Emissions, "Australia Japan Clean Hydrogen Trade Partnership," January 7, 2022, https://www.minister.industry.gov.au/ministers/taylor/media-releases/australia-japan-clean-hydrogen-trade-partnership#:~:text=The%20first%20round%20of%20the,%2C%E2%80%9D%20the%20Prime%20Minister%20said.

178 IEA, *Global Hydrogen Review 2023*, September 2023, p. 158, https://www.iea.org/reports/global-hydrogen-review-2023.

179 Hydrogen Intermediary Network Company (Hintco), "The H2Global Instrument," accessed March 5, 2024, https://h2-global.de/project/h2g-mechanism.

180 Joanna Sampson, *Hydrogen Insights 2023 December Update*, Hydrogen Council, December 12, 2023, p. 10, https://hydrogencouncil.com/en/hydrogen-insights-2023-december-update/.

181 IRENA and WTO, *International Trade and Green Hydrogen: Supporting the Global Transition to a Low-Carbon Economy*, December 2023, p. 21, https://www.irena.org/Publications/2023/Dec/International-trade-and-green-hydrogen-Supporting-the-global-transition-to-a-low-carbon-economy.

182 DIW Weekly Report 22/2023, Robin Sogalia, The New European Carbon border Adjustment Mechanism, https://www.diw.de/documents/publikationen/73/diw_01.c.873991.de/dwr-23-22-1.pdf.

183 Occupational Safety and Health Administration, "1910.103 - Hydrogen," accessed March 20, 2024, https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.103.

184 EFI, *The U.S. Hydrogen Demand Action Plan*, EFI Foundation, February 9, 2023, p. 82, https://efifoundation.org/reports/the-u-s-hydrogen-demand-action-plan-2/.

185 International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) Hydrogen Production Analysis Task Force, *Methodology for Determining the Greenhouse Gas Emissions Associated With the Production of Hydrogen*, July 2023, p. 39. https://www.iphe.net/_files/ugd/45185a_8f9608847cbe46c88c319a75bb85f436.pdf.

186 European Parliament, "Taxonomy: MEPs do not object to inclusion of gas and nuclear activities," July 6, 2022, https://www.europarl.europa.eu/news/en/press-room/20220701IPR34365/taxonomy-meps-do-not-object-to-inclusion-of-gas-and-nuclear-activities.

187 Jonathan Leclercq, "EU's CBAM: What do you need to do before July 2024 to avoid penalties for non-compliance?" DNV, https://www.dnv.com/supplychain/thought-leadership/eus-cbam-what-do-you-need-to-do-before-july-2024-to-avoid-penalties-for-non-compliance/.

188 European Commission, "Carbon Border Adjustment Mechanism," accessed March 8, 2024, https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en.

189 European Commission, "Carbon Border Adjustment Mechanism," accessed March 8, 2024, https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en.

190 European Commission, "Carbon Leakage," accessed March 8, 2024, https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/free-allocation/carbon-leakage_en.

191 European Commission, "Carbon Border Adjustment Mechanism," accessed March 8, 2024, https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en.

192 IEA, “Executive Summary – Ammonia Technology Roadmap – Analysis,” IEA, accessed March 8, 2024, https://www.iea.org/reports/ammonia-technology-roadmap/executive-summary.

193 https://e360.yale.edu/features/from-fertilizer-to-fuel-can-green-ammonia-be-a-climate-fix#:~:text=A%202021%20International%20Energy%20Agency,vital%20for%20the%20shipping

194 The Boston Consulting Group. "Harnessing the Potential of Renewable Ammonia," accessed July 8, 2024. https://www.bcg.com/publications/2023/harnessing-the-potential-of-renewable-ammonia.

195 The Boston Consulting Group. "Harnessing the Potential of Renewable Ammonia.” https://www.bcg.com/publications/2023/harnessing-the-potential-of-renewable-ammonia.

196 The Boston Consulting Group. "Harnessing the Potential of Renewable Ammonia." https://www.bcg.com/publications/2023/harnessing-the-potential-of-renewable-ammonia.

197 RTI International. "RTI International Awarded Funding from U.S. Department of Energy." https://www.rti.org/news/rti-international-awarded-funding-us-department-energy#:~:text=RTI%20has%20been%20awarded%20%2410,for%20use%20in%20agriculture.

198 Occupational Safety and Health Administration. "Safety Standards - Ammonia Refrigeration." https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.111

199 Environmental Protection Agency. "Safety Standards for Ammonia Refrigeration." Updated March 3, 2023. https://www.epa.gov/enforcement/safety-standards-ammonia-refrigeration#:~:text=,updated%20on%20March%203%2C%202023

200 AmmoniaKnowHow. "Review of Global Regulations for Anhydrous Ammonia Production, Use, and Storage." https://ammoniaknowhow.com/review-of-global-regulations-for-anhydrous-ammonia-production-use-and-storage/

201 DNV, "Harnessing Ammonia as Ship Fuel." https://www.dnv.com/expert-story/maritime-impact/Harnessing-ammonia-as-ship-fuel.html

202 The Boston Consulting Group. "Harnessing the Potential of Renewable Ammonia." https://www.bcg.com/publications/2023/harnessing-the-potential-of-renewable-ammonia.

203 DNV, "Methanol as a Potential Alternative Fuel for Shipping: A Brief Talk with Chris Chatterton." https://www.dnv.com/maritime/advisory/afi-update/Methanol-as-a-potential-alternative-fuel-for-shipping-A-brief-talk-with-Chris-Chatterton.html#:~:text=Methanol%20as%20shipping%20fuel%20has,place%20before%20committing%20large

204 DNV, "Methanol as an Alternative Fuel for Container Vessels." https://www.dnv.com/expert-story/maritime-impact/methanol-as-an-alternative-fuel-for-container-vessels.html#:~:text=The%20new%20IMO%20interim%20guidelines,fuelled%20ships

205 DNV, "Methanol as a Potential Alternative Fuel for Shipping: A Brief Talk with Chris Chatterton." https://www.dnv.com/maritime/advisory/afi-update/Methanol-as-a-potential-alternative-fuel-for-shipping-A-brief-talk-with-Chris-Chatterton.html

206 Joint Organizations Data Initiative (JODI), “FAQs about the Joint Organizations Data Initiative,” February 12, 2024, https://www.jodidata.org/about-jodi/faqs.aspx.

207 NEOM, “NEOM Green Hydrogen Company competes financial close at a total investment of USD 8.4Billion in the World’s Largest carbon-free green hydrogen plant,” May 22, 2023, https://www.neom.com/en-us/newsroom/neom-green-hydrogen-investment#:~:text=NEOM%20Green%20Hydrogen%20Company%20also%20secured%20an,venture%20between%20ACWA%20Power%2C%20Air%20Products%20and.

208 IEA, *Global Hydrogen Review 2023*, September 2023, p. 152, https://www.iea.org/reports/global-hydrogen-review-2023.

209 Kaula Nhongo, “Dutch Firms Partner With Namibia to Create Green-Hydrogen Sovereign Wealth Fund,” *Bloomberg*, June 20, 2023, https://www.bloomberg.com/news/articles/2023-06-20/dutch-firms-partner-namibia-to-create-sovereign-wealth-fund.

210 Joanna Sampson, “Global CEOs and Investors Join Forces to Accelerate Clean Hydrogen Industry,” *Hydrogen Council* (blog), June 22, 2023, https://hydrogencouncil.com/en/global-ceos-and-investors-join-forces-to-accelerate-clean-hydrogen-industry/.

211 Dolf Gielen et. al, “Unleashing the power of hydrogen for the Clean Energy Transition World Bank Blogs,” 2023, accessed February 6, 2024, https://blogs.worldbank.org/energy/unleashing-power-hydrogen-clean-energy-transition

212 Fairfield Consultancy Services OPC Pvt Ltd, “Hydrogen industry: Global report 2023 predicts market revenue to reach US$328 bn in 2030,” GlobelNewswire, 2023, accessed February 5, 2024, https://www.globenewswire.com/en/news-release/2023/07/17/2705933/0/en/Hydrogen-Industry-Global-Report-2023-Predicts-Market-Revenue-to-Reach-US-328-Bn-in-.

213 S&P Global, “Platts Hydrogen Price Wall,” accessed: 05 February 5, 2024, https://www.spglobal.com/commodityinsights/PlattsContent/_assets/_files/en/specialreports/energy-transition/platts-hydrogen-price-wall/index.html.

214 “Crude oil prices today (1970)” OilPrice.com, accessed February 6, 2024, https://oilprice.com/.

215 GEP, “Green & Blue Hydrogen: Current levelized cost of Production & Outlook,” GEP blog, 2016, accessed February 5, 2024, https://www.gep.com/blog/strategy/Green-and-blue-hydrogen-current-levelized-cost-of-production-and-outlook.

216 Hydrogen Council and McKinsey & Company, *Global Hydrogen Flows*, Hydrogen Council, December 2023, https://hydrogencouncil.com/wp-content/uploads/2023/12/Hydrogen-Insights-Dec-2023-Update.pdf.

217 Hydrogen Council and McKinsey & Company, *Global Hydrogen Flows*, Hydrogen Council, December 2023, https://hydrogencouncil.com/wp-content/uploads/2023/12/Hydrogen-Insights-Dec-2023-Update.pdf.

218 Hydrogen Council and McKinsey & Company, *Global Hydrogen Flows*, Hydrogen Council, December 2023, https://hydrogencouncil.com/wp-content/uploads/2023/12/Hydrogen-Insights-Dec-2023-Update.pdf.

219 Robert Liew, "Australia's Energy Revolution: The Promise of battery storage and hydrogen," Wood Mackenzie, 2023, accessed February 5, 2024, https://www.woodmac.com/news/opinion/australia-battery-storage-and-hydrogen/.

220 Taken from a PowerPoint presentation by the Hydrogen Exchange Initiative. (HYCLICX | Hyxchange). hyxchange.nl

221 Taken from a PowerPoint presentation by the Hydrogen Exchange Initiative. (HYCLICX | Hyxchange). hyxchange.nl

222 HYCXchange. "HYCLICX Renewable Price Indicator." https://hyxchange.nl/hyclicx/#:~:text=The%20renewable%20HYCLICX%20price%20indicator,a%20source%20for%20green%20hydrogen.

223 IEA, *Hydrogen – Breakthrough Agenda Report 2023* – analysis, 2023, accessed February 6, 2024, https://www.iea.org/reports/breakthrough-agenda-report-2023/hydrogen.

224 IEA, *Hydrogen – Breakthrough Agenda Report 2023* – analysis, 2023, accessed February 6, 2024, https://www.iea.org/reports/breakthrough-agenda-report-2023/hydrogen.

225 Hydrogen Council and McKinsey & Company, *Global Hydrogen Flows*, December 2023, https://hydrogencouncil.com/wp-content/uploads/2023/12/Hydrogen-Insights-Dec-2023-Update.pdf

226 Robert Liew, "Australia's Energy Revolution: The Promise of battery storage and hydrogen," Wood Mackenzie, 2023, accessed February 5, 2024, https://www.woodmac.com/news/opinion/australia-battery-storage-and-hydrogen/.

227 Robert Liew, "Australia's Energy Revolution: The Promise of battery storage and hydrogen," Wood Mackenzie, 2023, accessed February 5, 2024, https://www.woodmac.com/news/opinion/australia-battery-storage-and-hydrogen/.

228 IEA, *Hydrogen – Breakthrough Agenda Report 2023* – analysis, 2023, accessed February 6, 2024, https://www.iea.org/reports/breakthrough-agenda-report-2023/hydrogen.

229 IEA, *Hydrogen – Breakthrough Agenda Report 2023* – analysis, 2023, accessed February 6, 2024, https://www.iea.org/reports/breakthrough-agenda-report-2023/hydrogen.

230 Hydrogen Council and McKinsey & Company, *Global Hydrogen Flows*, December 2023, https://hydrogencouncil.com/wp-content/uploads/2023/12/Hydrogen-Insights-Dec-2023-Update.pdf.

231 Hydrogen Council and McKinsey & Company, *Global Hydrogen Flows*, December 2023, https://hydrogencouncil.com/wp-content/uploads/2023/12/Hydrogen-Insights-Dec-2023-Update.pdf.

232 BloombergNEF, "2H 2023 hydrogen market outlook: The demand question," 2023, accessed February 5, 2024, https://about.bnef.com/blog/2h-2023-hydrogen-market-outlook-the-demand-.

233 BloombergNEF, "2H 2023 hydrogen market outlook: The demand question," 2023, accessed February 5, 2024, https://about.bnef.com/blog/2h-2023-hydrogen-market-outlook-the-demand-.

234 Wilhelm Schmundt, *Building the green hydrogen economy*, Boston Consulting Group, accessed February 6, 2024, p. 19, https://web-assets.bcg.com/bc/82/a99c71144a60aa435736f574cffe/bcg-infrastructure-strategy-2023-building-the-green-hydrogen-economy-mar-2023-r.pdf.

235 Robert Gross et al., "How Long Does Innovation and Commercialisation in the Energy Sectors Take? Historical Case Studies of the Timescale from Invention to Widespread Commercialisation in Energy Supply and End Use Technology," Energy Policy 123 (2018): 682-699.

236 Clingendael International Energy Programme (CIEP), "Managing Future Security of Low Carbon Hydrogen Supply, understanding international value chain developments and market structures regarding security of supply.," The Hague, The Netherlands, July 2022.

237 Lance Brasher et al., "Growing opportunities in clean hydrogen: Insights," Skadden, Arps, Slate, Meagher & Flom LLP, 2022, accessed February 6, 2024, https://www.skadden.com/insights/publications/2022/09/quarterly-insights/growing-opportunities-in-clean-hydrogen.

238 Lance Brasher et al., "Growing opportunities in clean hydrogen: Insights," Skadden, Arps, Slate, Meagher & Flom LLP, 2022, accessed February 6, 2024, https://www.skadden.com/insights/publications/2022/09/quarterly-insights/growing-opportunities-in-clean-hydrogen.

239 S&P Global Commodity Insights, "Ørsted surprises with US offshore write-down scale as analysts welcome clarity", 2023, https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/216-rsted-surprises-with-us-offshore-write-down-scale-as-analysts-welcome-clarity-78194923.

240 Greg Ip, “Why no one wants to pay for the green transition,” *Wall Street Journal*, 2023, accessed February 6, 2024, https://www.wsj.com/business/autos/why-no-one-wants-to-pay-for-the-green-transition-aed6ba74.

241 C. Rouillé, “Unveiling the power of hydrogen in Europe: It’s time to execute,” *POLITICO*, 2023, accessed February 6, 2024, https://www.politico.eu/sponsored-content/unveiling-the-power-of-hydrogen-in-europe-its-time-to-execute/

242 Francesco La Camera and Rabab Fatima, *Scaling up Renewables in Landlocked Developing Countries*, IRENA, https://www.irena.org/Publications/2022/Sep/Scaling-up-renewables-in-landlocked-developing-countries.

243 Flor Lucia De la Cruz, “Hydrogen: The US$600 billion investment opportunity,” Wood Mackenzie, 2022, accessed February 6, 2024, https://www.woodmac.com/news/opinion/hydrogen-the-us$600-billion-investment-opportunity/.

244 IEA, *Hydrogen – Breakthrough Agenda Report 2023* – analysis, 2023, accessed February 6, 2024, p. 57, https://www.iea.org/reports/breakthrough-agenda-report-2023/hydrogen.

245 Susana Moreira and Tim Laing, *Sufficiency, Sustainability, and Circularity of Critical Materials for Clean Hydrogen*, World Bank-Hydrogen Council, 2022, https://hydrogencouncil.com/en/sufficiency-sustainability-and-circularity-of-critical-materials-for-clean-hydrogen/.

246 Nature Communications. "The mining industry is an essential sector of the economy." https://www.nature.com/articles/s41467-020-18661-9#:~:text=The%20mining%20industry%20is%20an,The%20synergies%20and%20trade

247 MIT Climate Portal. "Will mining resources needed for clean energy cause problems for the environment?" https://climate.mit.edu/ask-mit/will-mining-resources-needed-clean-energy-cause-problems-environment.

248 MIT Climate Portal. "Will mining resources needed for clean energy cause problems for the environment?" https://climate.mit.edu/ask-mit/will-mining-resources-needed-clean-energy-cause-problems-environment.

249 MIT Climate Portal. "Will mining resources needed for clean energy cause problems for the environment?" https://climate.mit.edu/ask-mit/will-mining-resources-needed-clean-energy-cause-problems-environment.

250 MIT Climate Portal. "Will mining resources needed for clean energy cause problems for the environment?" https://climate.mit.edu/ask-mit/will-mining-resources-needed-clean-energy-cause-problems-environment.

251 Hydrogen Council and McKinsey & Company, *Global Hydrogen Flows*, December 2023, p. 6, https://hydrogencouncil.com/wp-content/uploads/2023/12/Hydrogen-Insights-Dec-2023-Update.pdf.

252 Hydrogen Council and McKinsey & Company, *Global Hydrogen Flows*, December 2023, p. 6, https://hydrogencouncil.com/wp-content/uploads/2023/12/Hydrogen-Insights-Dec-2023-Update.pdf.

253 Hydrogen Council and McKinsey & Company, *Hydrogen Insights 2024,* September 2024, pp. 4 and 8, https://hydrogencouncil.com/wp-content/uploads/2024/09/Hydrogen-Insights-2024.pdf.

254 Hydrogen Council and McKinsey & Company, *Hydrogen Insights 2024*, September 2024, pp. 4 and 8, https://hydrogencouncil.com/wp-content/uploads/2024/09/Hydrogen-Insights-2024.pdf.

255 Hydrogen Council and McKinsey & Company, *Global Hydrogen Flows*, December 2023, https://hydrogencouncil.com/wp-content/uploads/2023/12/Hydrogen-Insights-Dec-2023-Update.pdf.

256 Fairfield Consultancy Services OPC Pvt Ltd, “Hydrogen industry: Global report 2023 predicts market revenue to reach US$328 bn in 2030,” *GlobeNewswire*, 2023, accessed February 6, 2024, https://www.globenewswire.com/en/news-release/2023/07/17/2705933/0/en/Hydrogen-Industry-Global-Report-2023-Predicts-Market-Revenue-to-Reach-US-328-Bn-in-2030.

257 Hydrogen Council and McKinsey & Company, *Global Hydrogen Flows*, December 2023, https://hydrogencouncil.com/wp-content/uploads/2023/05/Hydrogen-Insights-2023.pdf.

258 IEA, Hydrogen – *Breakthrough Agenda Report 2023* – analysis, 2023, accessed February 6, 2024, https://www.iea.org/reports/breakthrough-agenda-report-2023/hydrogen.

259 C. Palladino, “Lex in depth: the staggering cost of a green hydrogen economy,” *Financial Times*, 2023, accessed February 2024, https://www.ft.com/content/6e22930b-a007-4729-951f-78d6685a7514.

260 BloombergNEF, “2H 2023 hydrogen market outlook: The demand question,” 2023, accessed February 5, 2024, https://about.bnef.com/blog/2h-2023-hydrogen-market-outlook-the-demand-.

261 Hydrogen Council and McKinsey & Company, *Global Hydrogen Flows*, December 2023, p. 8, https://hydrogencouncil.com/wp-content/uploads/2023/12/Hydrogen-Insights-Dec-2023-Update.pdf.

262 Hydrogen Council and McKinsey & Company, *Global Hydrogen Flows*, December 2023, p. 13, https://hydrogencouncil.com/wp-content/uploads/2023/12/Hydrogen-Insights-Dec-2023-Update.pdf.

263 Hydrogen Council and McKinsey & Company, *Global Hydrogen Flows*, December 2023, p. 13, https://hydrogencouncil.com/wp-content/uploads/2023/12/Hydrogen-Insights-Dec-2023-Update.pdf.

264 Mathias Zacarias and Jane Nakano, "Exploring the hydrogen midstream: Distribution and delivery," CSIS, 2003, accessed February 6, 2024, https://www.csis.org/analysis/exploring-hydrogen-midstream-distribution-and-delivery.

265 Mathias Zacarias and Jane Nakano, "Exploring the hydrogen midstream: Distribution and delivery," CSIS, 2003, accessed February 6, 2024, https://www.csis.org/analysis/exploring-hydrogen-midstream-distribution-and-delivery.

266 Phred Dvorak, "Fertilizer Companies Are Betting on Ammonia as a Low-Carbon Fuel," *The Wall Street Journal*, 2023, accessed February 6, 2024. https://www.wsj.com/business/energy-oil/fertilizer-ammonia-low-carbon-fuel-a287902b.

267 IEA, Hydrogen – *Breakthrough Agenda Report 2023* – analysis, 2003, accessed February 6, 2024, https://www.iea.org/reports/breakthrough-agenda-report-2023/hydrogen.

268 Robert Liew et al., "Australia's Energy Revolution: The Promise of battery storage and hydrogen," Wood Mackenzie, 2003, February 5, 2024, https://www.woodmac.com/news/opinion/australia-battery-storage-and-hydrogen/.

269 Robert Liew et al., "Australia's Energy Revolution: The Promise of battery storage and hydrogen," Wood Mackenzie, 2003, February 5, 2024, https://www.woodmac.com/news/opinion/australia-battery-storage-and-hydrogen/.

270 "Clean hydrogen collaboration with Japan," Australian Government Department of Foreign Affairs and Trade, 2022, accessed February 21, 2024, https://www.dfat.gov.au/about-us/publications/trade-investment/business-envoy/business-envoy-february-2022/clean-hydrogen-collaboration-japan.

271 "Clean hydrogen collaboration with Japan," Australian Government Department of Foreign Affairs and Trade, 2022, accessed February 21, 2024, https://www.dfat.gov.au/about-us/publications/trade-investment/business-envoy/business-envoy-february-2022/clean-hydrogen-collaboration-japan.

272 "Riyadh, Tokyo to cooperate on energy security, hydrogen and ammonia, " Joint Statement on KSA-Japan Lighthouse Initiative for Clean Energy Cooperation, *Reuters*, accessed February 21, 2024, https://www.reuters.com/business/energy/saudi-arabia-maintains-support-japan-energy-partnership-2023-07-16/

273 "Riyadh, Tokyo to cooperate on energy security, hydrogen and ammonia, "Joint Statement on KSA-Japan Lighthouse Initiative for Clean Energy Cooperation, accessed February 21, 2024, https://www.reuters.com/business/energy/saudi-arabia-maintains-support-japan-energy-partnership-2023-07-16/.

274 C. Palladino, "Lex in depth: the staggering cost of a green hydrogen economy," *Financial Times*, 2023, February 2024, https://www.ft.com/content/6e22930b-a007-4729-951f-78d6685a7514.

275 Siri Hedreen, "Gray hydrogen customers slow to go green, so US developers Chase Overseas Demand," S&P Global homepage, 2023, accessed February 6, 2024, https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/gray-hydrogen-customers-slow-to-go-green-so-us-developers-chase-overseas-demand-75971482.

276 Siri Hedreen, "Gray hydrogen customers slow to go green, so US developers Chase Overseas Demand," S&P Global homepage, 2023, accessed February 6, 2024, https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/gray-hydrogen-customers-slow-to-go-green-so-us-developers-chase-overseas-demand-75971482.

277 IEA, Hydrogen – *Breakthrough Agenda Report 2023* – analysis, 2023, accessed February 6, 2024, https://www.iea.org/reports/breakthrough-agenda-report-2023/hydrogen.

278 Dan Esposito and Hadley Tallackson, "The inflation reduction act upends hydrogen economics with opportunities, pitfalls," *Utility Dive*, 2022, accessed February 6, 2024, https://www.utilitydive.com/news/the-ira-will-accelerate-electrolyzed-hydrogens-future-heres-what-that-me/632925/.

279 Dan Esposito and Hadley Tallackson, "The inflation reduction act upends hydrogen economics with opportunities, pitfalls," *Utility Dive*, 2022, accessed February 6, 2024, https://www.utilitydive.com/news/the-ira-will-accelerate-electrolyzed-hydrogens-future-heres-what-that-me/632925/.

280 The White House, December 22, 2023, Treasury Sets out Proposed Rules for Transformative Clean Hydrogen Incentives, https://www.whitehouse.gov/cleanenergy/clean-energy-updates/2023/12/22/treasury-sets-out-proposed-rules-for-transformative-clean-hydrogen-incentives/.

281 IRS, Treasury, IRS issue guidance on the tax credit for the production of clean hydrogen, December 22, 2023, https://www.irs.gov/newsroom/treasury-irs-issue-guidance-on-the-tax-credit-for-the-production-of-clean-hydrogen.

282 National Archives, Federal Register, Proposed Rule by the Internal Revenue Service– Section 45V Credit for Production of Clean Hydrogen; Section 48(a)(15) Election to Treat Clean Hydrogen Production Facilities as Energy Property, https://www.federalregister.gov/documents/2024/04/11/2024-07644/section-45v-credit-for-production-of-clean-hydrogen-section-48a15-election-to-treat-clean-hydrogen.

283 National Archives, Federal Register, Proposed Rule by the Internal Revenue Service, "Section 45V Credit for Production of Clean Hydrogen; Section 48(a)(15) Election to Treat Clean Hydrogen Production Facilities as Energy Property," https://www.federalregister.gov/documents/2024/04/11/2024-07644/section-45v-credit-for-production-of-clean-hydrogen-section-48a15-election-to-treat-clean-hydrogen.

284 U.S. Department of Energy, Office of Clean Energy Demonstrations, DOE Establishes Bipartisan Infrastructure Law's $9.5 Billion Clean Hydrogen Initiatives, Department of Energy. https://www.energy.gov/oced/regional-clean-hydrogen-hubs-0#:~:text=The%20Regional%20Clean%20Hydrogen%20Hubs%20will%20create%20networks%20of%20hydrogen,store%20tremendous%20amounts%20of%20energy.

285 Polly Martin, "Fortescue takes final investment decision on first two hydrogen production projects worth a combined $700M, Hydrogen news and intelligence," *Hydrogeninsight*, accessed February 6, 2024, https://www.hydrogeninsight.com/production/fortescue-takes-final-investment-decision-on-first-two-hydrogen-production-projects-worth-a-combined-700m/2-1-1557992?zephr_sso_ott=asEoji.

286 Hydrogen Council and McKinsey & Company, *Global Hydrogen Flows*, December 2023, P. 8, https://hydrogencouncil.com/wp-content/uploads/2023/12/Hydrogen-Insights-Dec-2023-Update.pdf.

287 Hydrogen Council and McKinsey & Company, *Global Hydrogen Flows*, December 2023, p. 17, https://hydrogencouncil.com/wp-content/uploads/2023/12/Hydrogen-Insights-Dec-2023-Update.pdf

288 Nikolaus J. Kurmayer, "EU agrees new rules for investments into hydrogen infrastructure," euractiv.com, 2023, February 6, 2024, https://www.euractiv.com/section/energy-environment/news/eu-agrees-new-rules-for-investments-into-hydrogen-infrastructure.

289 C. Palladino, "Lex in depth: the staggering cost of a green hydrogen economy," *Financial Times*, 2023, accessed February 2024, https://www.ft.com/content/6e22930b-a007-4729-951f-78d6685a7514.

290 Central Energy Resources Center, "World Oil and Gas Resource Assessments," USGS, April 26, 2019, https://www.usgs.gov/centers/central-energy-resources-science-center/science/world-oil-and-gas-resource-assessments.

291 Ken Medlock, "The Shale Gas Revolution and What It Means for Global Energy Markets," presentation, Baker Institute, Houston, Texas, March 2, 2010,

292 Richard Newell, "Annual Energy Outlook 2010," presentation, March 2, 2010.

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The Energy Futures Initiative advances science-based solutions to climate change through evidence-based analysis, thought leadership, and coalition building.

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King Abdullah Petroleum Studies and Research Center (KAPSARC) is an advisory think tank within global energy economics and sustainability providing services to entities and authorities in the Saudi energy sector.

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