Hydrogen Market Formation: An Evaluation Framework

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EFI FOUNDATION

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Introduction

Hydrogen is a versatile clean energy carrier that offers the global economy the flexibility to rapidly decarbonize existing industries as well as the scalability to transition to new energy pathways. These properties make hydrogen a critical option for reaching economywide net-zero emissions.

While hydrogen is used mostly in the petrochemical and fertilizer industries, there is growing investment and policy activity in several regions—including the United States, Canada, the European Union, the U.K., Japan, and China—to expand clean hydrogen production and end use. These countries represent over half of the global hydrogen market today and have policy targets for up to 40 million metric tons per year (Mt/yr) of clean hydrogen production by 2030.[a, 1]

The level of global interest in hydrogen has never been higher. One industry association tracked more than 1,000 clean hydrogen project proposals as of January 2023, representing 38 Mt/yr of new clean supply.[2] The EFI Foundation is tracking 440 clean hydrogen projects in the United States alone.[3] However, only a handful of projects have reached final investment decisions –one estimate finds roughly 0.06 Mt/yr of clean hydrogen production in operation today—because of market uncertainty, high technology costs, and a range of other issues that will be discussed below.[4]

Most new clean hydrogen projects integrate supply and demand—often with limited or no midstream infrastructure.[5] In the United States, a focus on clean hydrogen hubs aims to address such connectivity issues. In China, the lack of hydrogen pipelines connecting hydrogen supply in the west with demand centers in the east is hindering the production of renewable-based hydrogen. Repurposing existing infrastructure to foster hydrogen market development is one pathway. In the U.K., where 85% of buildings are connected to the natural gas network, ongoing industry trials to demonstrate safety will determine whether

[a] Equivalent to 33% of electricity consumption in the United States in 2022. Source: U.S. Energy Information Administration, "Electricity Explained: Use of Electricity," April 20, 2023, https://www.eia.gov/energyexplained/electricity/use-of-electricity.php.

blending up to 20% hydrogen by volume into the Great Britain gas distribution networks will be allowed. Blending studies are underway in the EU, where the European Hydrogen Backbone has great potential to connect demand and supply centers over long distances. However, many issues, including infrastructure variability, emissions reduction concerns, and roundtrip efficiency challenges across the continent make converting existing gas networks to hydrogen challenging. Japan and Canada are focusing on hydrogen imports and exports, respectively, but a global clean hydrogen market is still in its infancy.

At this stage of hydrogen market development, it is crucial that policymakers and investors support projects to move the industry up the learning curve and drive down technology costs. The EFI Foundation developed a three-layer Evaluation Framework to help first movers, investors, and policymakers analyze fundamental conditions that can enable clean hydrogen's market development. The framework's three layers of analysis apply to any potential or emerging hydrogen market in the world.

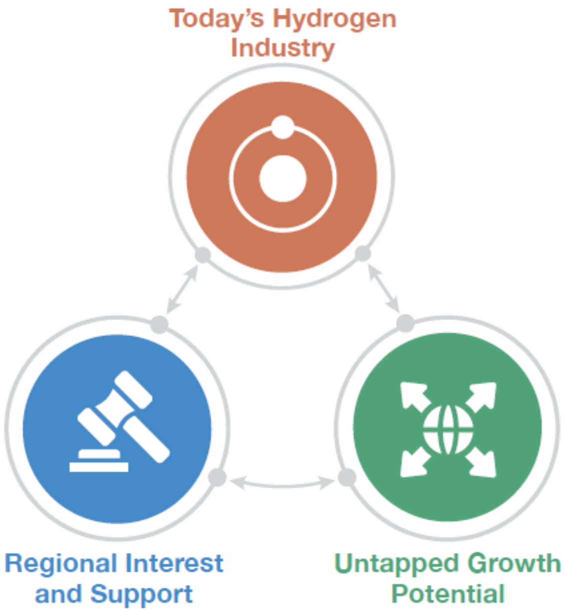
Hydrogen Market Potential Evaluation Framework

The EFI Foundation's three-layer Evaluation Framework (Figure 1) is designed to help first movers, investors, and policymakers navigate the dynamic hydrogen business and policy environment to pinpoint new opportunities and challenges in a region based on:

1) **Today's Hydrogen Industry,** defined as a region's current hydrogen industries and activities across the hydrogen value chain.
2) **Regional Interest and Support,** defined as a region's current explicit and implicit interest in hydrogen from policymakers, industry leaders, and local communities.
3) **Untapped Growth Potential,** defined as a region's natural, human, and engineered resources that may be leveraged to support hydrogen industry scalability and market formation.

Figure 1.

Evaluation Framework: Core factors for analyzing a dynamic business and policy landscape



The three primary factors in the Hydrogen Market Evaluation Framework interact inconsequentially and focus on elements that are essential to developing a clean hydrogen market in a given location.

The Market Evaluation Framework includes a series of questions designed to help investors and policymakers assess the hydrogen market potential of any region, exploring opportunities and challenges across the entire hydrogen value chain (Figure 2). Hydrogen markets will form around various objectives and capabilities worldwide.

To spur participation in emerging hydrogen markets, this framework seeks to bridge the information gap between current industries and capabilities and future growth potential within regions. It synthesizes large amounts of information on characteristics of hydrogen markets to create user-friendly guidance on what to look for in terms of growth potential. These questions provide background information to guide stakeholders in finding the characteristics that will be most important for market formation within regions. Region-specific examples are provided for the United States, Canada, the EU, the U.K., Japan, and China to illustrate how this framework may be used.

Figure 2.
Evaluation Framework questions

Today's Hydrogen Industry

1. What are the current uses for hydrogen?
2. How is hydrogen currently produced?
3. Is current hydrogen demand co-located with supply?
4. Is there existing hydrogen transport, distribution, and storage infrastructure?
5. Are there existing regional infrastructures that could be converted to hydrogen compatible?
6. How are institutions in the energy and industrial sectors structured?
7. How have the energy and hydrogen industries historically operated with local communities?

Regional Interest and Support

1. Is there a national and/or regional decarbonization plan?
2. Is there a national and/or regional clean hydrogen strategy?
3. Are there existing regulations for clean hydrogen?
4. Are there active policy incentives for clean hydrogen?
5. What public statements are available that indicate the interests, plans, or specific actions of the potential clean hydrogen market participants?
6. What are the plans to expand clean hydrogen use in the region, and is there announced interest from private capital to support development?
7. What are local communities' views on clean hydrogen?

Untapped Growth Potential

1. Are there energy and other input sources for clean hydrogen production?
2. What is the potential demand for clean hydrogen in end-use market sectors?
3. To what extent can existing end-use assets be converted to clean hydrogen, either 100% or as blended with natural gas?
4. What is the feasibility of expanding the supply chain needed to support increased supply? Are there particular challenges in either critical materials, manufacturing, or construction?
5. What human and knowledge resources are needed to support clean hydrogen market development on the planned scale?
6. How can the current workforce in fossil-fuel and adjacent industries transition and contribute to developing the clean hydrogen industry?
7. What public and private sector support for innovation are available that either have current or the potential to support RD&D and future deployment of clean hydrogen technologies?

The 21 questions in the Hydrogen Market Evaluation Framework are designed to assess a location's potential to develop a clean hydrogen market. The questions are listed in no particular order and center on elements in today's hydrogen industry that can be scaled up in the development of a broader clean hydrogen market; regional interest and support that enables clean hydrogen adoption; and untapped growth potential that can foster clean hydrogen market formation.

Today's Hydrogen Industry

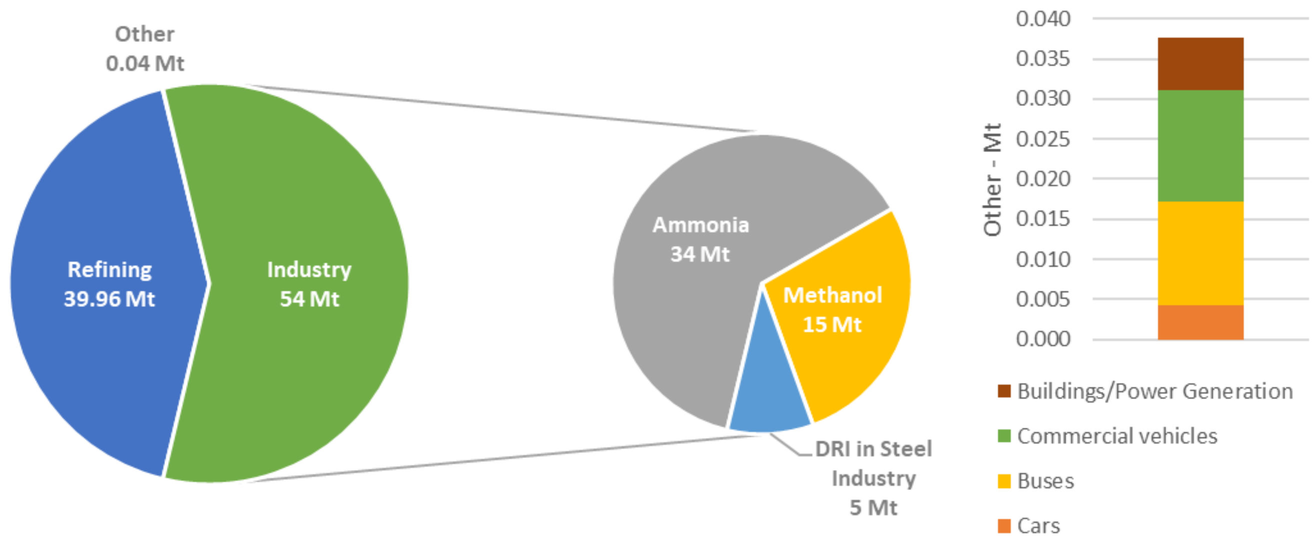
The first layer of the framework is designed to identify a region's current hydrogen infrastructure and business activities. These may include existing hydrogen production and demand, including the scale and distribution of each; hydrogen storage; and hydrogen transportation infrastructure. Assessing market conditions helps to narrow the potential market segments where new investments may be made. In addition, evaluating community engagement with the existing energy and hydrogen industries informs the prospects of future hydrogen investments.

1. **What are the current uses for hydrogen?**

Current worldwide hydrogen demand is 94 Mt and concentrates in industrial applications such as fuel, chemical, and fertilizer production (Figure 3).[6] Hydrogen use is gaining traction in other sectors including transportation, heavy industry, power generation, buildings, and production of hydrogen-derived fuels (e.g., ammonia and methanol in fuel applications, synthetic methane, and Fischer-Tropsch fuels[b]). Nevertheless, these applications are nascent, accounting for around 0.04% of global hydrogen demand.[7]

Most new demand interest is coming from the transportation sector. Fueling stations for passenger vehicles are still a slow-growing demand, but the use of hydrogen in warehouse forklifts and airport ground transportation is increasing around the globe.[8]

Figure 3.
Global hydrogen demand in 2021, million metric tons (Mt)



[b] Fischer–Tropsch fuels are produced through the process of converting a mixture of hydrogen and carbon monoxide into liquid hydrocarbons.

This graph shows hydrogen demand in 2021. Hydrogen is used in refineries to remove impurities such as sulfur and to upgrade crude oil into lighter products. It also is used to produce ammonia, which is a feedstock in fertilizer production, and to produce methanol, which is used as a feedstock to produce chemicals and products such as plastics and fuels. Hydrogen also is used in steel production, in which iron ore is reduced with hydrogen to produce direct reduced iron (DRI). The bar chart displays other hydrogen demand. Transportation accounts for most of the remaining hydrogen demand, although in limited quantities, comparatively. Source: See first figure mention in text for sources.

2. How is hydrogen currently produced?

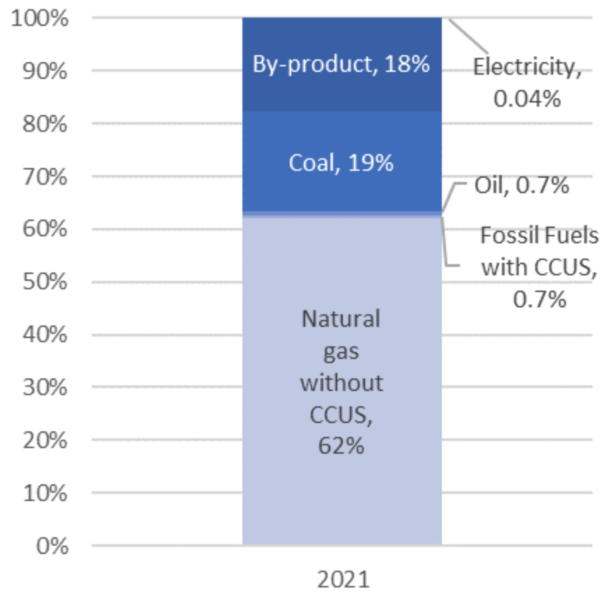
The adoption of hydrogen as an energy carrier depends on a reliable and cost-effective supply. The existence of hydrogen production at a local or regional level signals to the market that current expertise and capacity can be scaled up as adoption takes place.

Current hydrogen production infrastructure must be further evaluated while considering the needs of future hydrogen demand. Analysis of existing hydrogen production capacity should include the production technology, condition, and life span of the facility. The production technology and feedstock used are especially important in assessing the carbon intensity of the hydrogen produced.

Today, most hydrogen is produced from unabated fossil fuels (Figure 4), emitting carbon dioxide (CO_2).[9] The present production scale and the capacity at which this scale is utilized will reveal the opportunity for expansion. Finally, the production type—centralized vs. distributed—indicates the transport and storage infrastructure requirements. The proximity of the existing production facilities to their intended end uses can greatly reduce the time and investment needed.

Figure 4.

Global hydrogen production mix in 2021, percentage



Most of the hydrogen produced in 2021 (94 Mt) was derived from unabated fossil fuels, which emitted more than 900 Mt of CO_2. Natural gas is the most used feedstock to produce hydrogen, followed by coal. Hydrogen is also a byproduct of naphtha reforming at refineries. Low-carbon hydrogen, produced from electricity via water electrolysis or fossil fuels with CCUS, accounted for less than 1% of total hydrogen production. Adapted from: See first figure mention in text for sources.

3. Is current hydrogen demand co-located with supply?

Hydrogen production for industrial applications, such as refineries, is commonly co-located with demand. For uses where hydrogen is a primary feedstock, it is often produced on location in captive hydrogen plants. However, there are several examples, mostly in the United States, where hydrogen is produced in large-scale central plants serving multiple industrial plants.[10] Moreover, hydrogen production and utilization are integrated to optimize the overall system efficiency.

The close link between supply and demand constitutes a challenge for tapping into the hydrogen supply from these facilities for other applications. In other configurations, hydrogen production is decoupled from end-use applications. One example is industrial parks where large-scale hydrogen production facilities supply hydrogen to multiple end users. This approach, which can be referred to as a "hydrogen hub," opens immense potential for expanding the use of hydrogen in different applications. In a survey of more than 30 global hydrogen hubs, over 65% reported supplying more than one end-use sector.[11]

4. Is there existing hydrogen transport, distribution, and storage infrastructure?

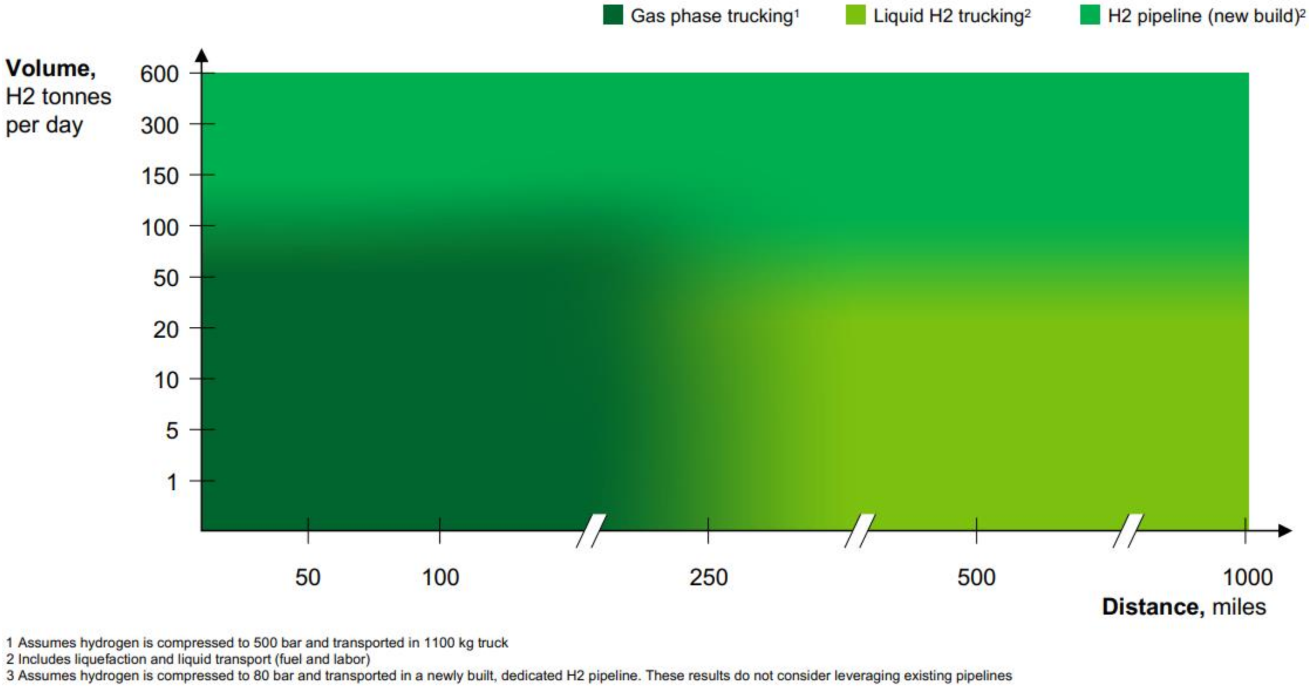
Widespread adoption of hydrogen in the energy system is, in part, limited by the lack of transport and storage infrastructure. Because future hydrogen demand is not expected to always be co-located with supply, the consideration of such infrastructure is a vital element in developing a hydrogen-based economy.

The U.S. Department of Energy sees hydrogen infrastructure developing as markets grow: "[As] hydrogen production costs [fall], driven by economies of scale and R&D … privately funded hydrogen infrastructure projects will come online."[12] Hydrogen transport infrastructure may exist in different types and scales (Figure 5).[13] While a network of transport and distribution pipelines might be used, other direct hydrogen transport methods, such as rail or truck, or indirect transport options using hydrogen carriers, such as ammonia or methanol, should be considered.[c,14] An important piece of the transport infrastructure is the conditioning and pressurization requirement for fueling applications.

For renewable-based hydrogen production, hydrogen storage can compensate for the variability in production due to feedstock intermittency. Reliable hydrogen supply for several end-use applications will depend on local storage availability or connection to other regions. The existence of hydrogen distribution and its expandability will facilitate hydrogen's adoption in novel applications.

[c] Ammonia is produced when hydrogen and carbon dioxide undergo a process called methanation. Ammonia is considered a hydrogen carrier because it can be decomposed, or cracked, back into hydrogen using a catalyst. Methanol is produced when pure hydrogen goes through a methanol reactor. It can also be converted back to hydrogen.

Figure 5.
Preferred hydrogen distribution method by volume and distance



Distance between production facilities and demand locations, as well as volume, influence the preferred method of transporting hydrogen. Transportation options include trucking, which can transport either liquid or gaseous hydrogen, and pipelines. Source: See first figure mention in text for sources.

5. **Are there existing regional energy infrastructures that could be converted to hydrogen-compatible?**

A multitude of regional infrastructure elements need to be in place to support a clean hydrogen system. There are three main categories of compatibility: clean hydrogen transport, low-carbon power grid, and liquefied natural gas (LNG) import/export terminals. For hydrogen transport, natural gas pipelines can be retrofitted for use.[15] Anywhere from 5% to 20% of hydrogen blending—or integrating concentrations of hydrogen into natural gas pipelines—is claimed to be technically feasible with existing transmission and distribution infrastructure.[16] At higher blending concentrations, steel pipe degradation, or embrittlement, may occur. Hydrogen is also much lighter than methane, so leakage also must be mitigated.[17] Research on coatings as well as advanced testing of different pipeline materials is being conducted to determine how much blending is possible (see the case studies section of this report).

With the widespread adoption of hydrogen, international low-carbon hydrogen trade is expected to develop using liquefied hydrogen or a hydrogen carrier such as ammonia. The availability of import and export terminals will be an important factor in determining international trade routes. The closest and potentially most compatible options today are LNG terminals that can be converted or co-used as hydrogen terminals. However, conversion is still expensive because new tanks that can support the lower temperature needs of hydrogen can cost 1.5 times more than LNG tanks, which in turn represent about half the total cost of an LNG terminal.[18]

Finally, the power grid will be a crucial determinant of hydrogen expansion. Electricity is required to produce hydrogen via electrolysis and to operate the methane reformation facility, and for the conditioning and pressurization of hydrogen. Expansion of a power grid with a high penetration of intermittent renewable energy sources requires the existence of energy storage at different time scales to ensure grid reliability.

6. How are institutions in the energy and industrial sectors structured?

Energy and industrial sectors are governed by regulatory, policy, and jurisdictional environments that may support or hinder hydrogen market development.

In the United States, for example, there are federal, state, and local governments that exert strong influence over how electricity and natural gas industries and markets operate. The oil sector, however, is governed differently across the value chain of production, delivery, export, and final consumption. It is important to understand the current dynamics of the energy and industrial sector regulations and structures to determine the best path forward for hydrogen investment.

7. How have the energy and hydrogen industries historically operated with local communities?

Future clean hydrogen development would benefit from engagement with and participation from local communities. Understanding how relationships between energy and hydrogen project developers and local communities have played out will allow potential investors to identify areas of sensitivity that need to be addressed, thus contributing to future inclusive growth of a nascent hydrogen industry.

Historically, have communities been engaged in energy and hydrogen project development? What was the extent of such engagement? For energy and hydrogen projects to develop, was it necessary to receive communities' consent in the form of agreements or binding plans? Have the energy or hydrogen project developments generated positive or negative impacts for the communities where they were located? Which type of impact (e.g., environmental, social, other)? If applicable, when communities raised concerns about adverse consequences of energy or hydrogen project development, how were such concerns addressed?

Regional Interest and Support

The second layer of the framework defines the current regional interest from policymakers, industry leaders, and local communities in expanding their hydrogen sector. The primary indicators of interest include government policies and other signals of public support, private sector activities, communities' views about hydrogen development, and the level of regional needs for a low-carbon resource like hydrogen. Levels of interest vary, from the availability of regional hydrogen strategy/goals to the existence of incentives.

1. **Is there a national and/or regional decarbonization plan?**

The main driver for large-scale adoption of clean hydrogen is decarbonization. Clean hydrogen has been introduced as a decarbonization tool alongside electrification, carbon capture and storage, and clean electricity resources (e.g., solar, wind, and nuclear), among many others. The deployment of clean hydrogen will be correlated to a location's decarbonization plan, in particular its sector-specific targets. Clearly pledged environmental targets reveal a regional commitment for furthering clean hydrogen's market development potential.

Several national climate action plans include an examination of hydrogen's role in achieving emissions-reduction targets. Sectoral decarbonization plans (e.g., industry, transportation) or policies to ban polluting technologies (e.g., internal combustion engine vehicles) also can contribute to interest in hydrogen. Countries' joint pledges to adopt hydrogen as a decarbonization tool are an indicator of interest and support as well. For instance, the Group of Seven countries have announced the G7 Hydrogen Action Pact to accelerate the development of low-carbon and renewable hydrogen. [d,19]

2. **Is there a national and/or regional clean hydrogen strategy?**

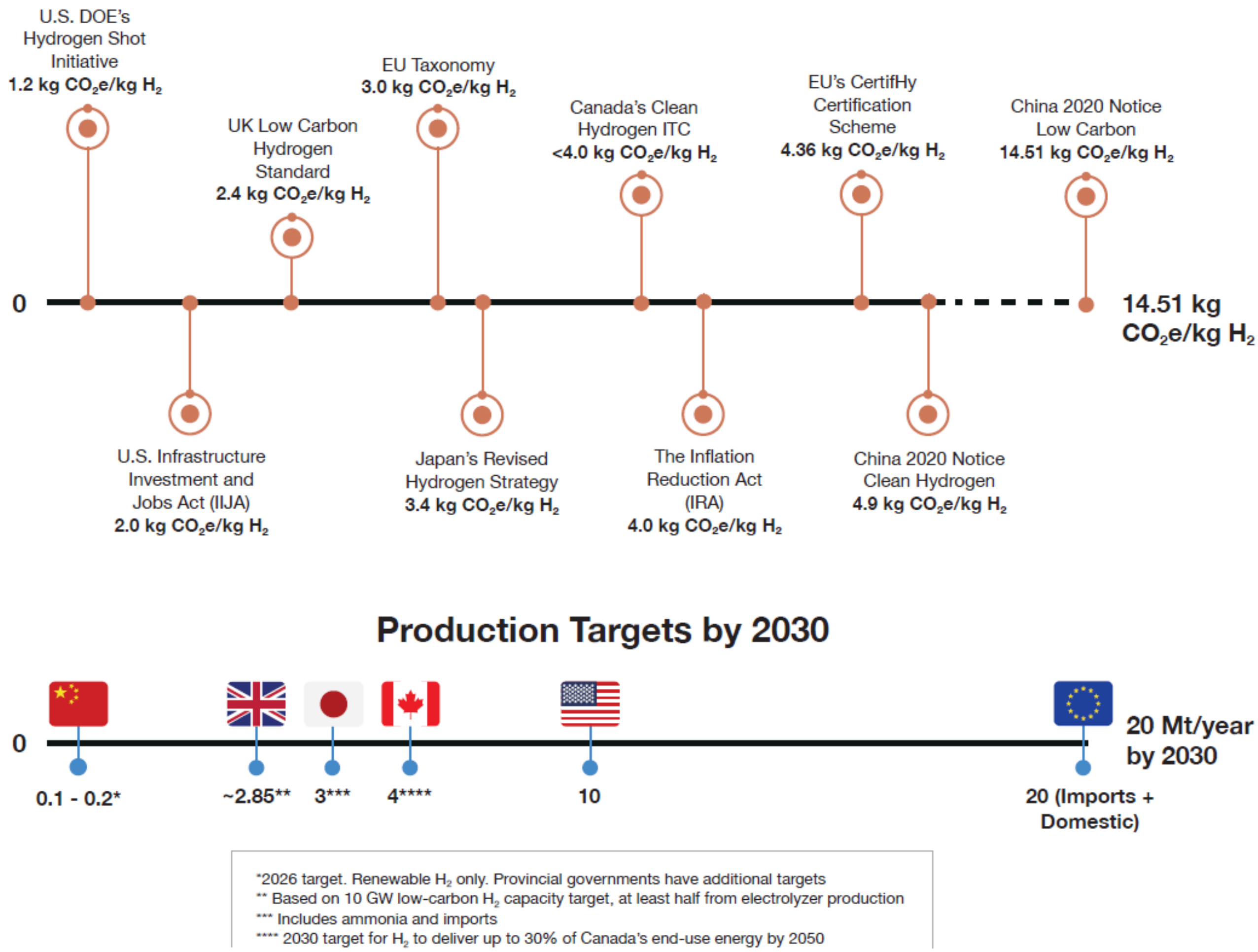
A clear indication of regional interest and support for clean hydrogen is a comprehensive hydrogen strategy including explicit targets for the country/region and for sectors or industries. The availability of incentive structures within the strategy for market formation, such as for seeding hydrogen hubs, also is a positive indication. For example, as of July 2022, at least 48 countries have announced national hydrogen strategies or road maps.[20] These strategies can often be found on the website of a government's energy ministry.

Some national strategies include hydrogen-specific technology road maps spanning supply-side targets, life cycle emissions requirements (Figure 6), and end-use priorities.[21,22,23,24,25,26,27,28,29] Some strategies span the entire supply chain from production to end use, while others focus on specific areas such as pipeline retrofits. Clean hydrogen strategies provide a vision about future hydrogen adoption and signal to interested stakeholders the direction and scope of market development.

[d] G7 countries: Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States, as well as the European Union.

Figure 6.

Definitions of clean hydrogen and 2030 production targets by region



Definitions of clean hydrogen vary by region and policy, focusing on life cycle or emissions at the site of production. The figure also lists clean hydrogen production targets by country by 2030. Some of these countries have production targets beyond this time frame (e.g., U.S.: 20 Mt by 2040 and 50 Mt by 2050; Japan: 12 Mt by 2040 and 20 Mt by 2050). Adapted from: See first figure mention in text for sources.

3. Are there existing regulations for clean hydrogen?

In countries where hydrogen is used today, there are regulatory systems governing its use as a chemical feedstock and fuel. However, further adoption of hydrogen as a clean fuel may require new regulatory frameworks, certification programs, and standards to create certainty for stakeholders. For instance, defining a methodology to calculate the carbon footprint of hydrogen is necessary to ensure low-carbon production.[30] Defining such methodology is not only important to deliver on climate goals but also is fundamental to developing a global hydrogen market.[31]

Clear standards and regulations for hydrogen refueling stations also could reduce barriers to adoption in the transportation sector. Additionally, because hydrogen has been used mostly as a feedstock, certain locations must adapt regulations to treat hydrogen as a fuel. For instance, in the United States, hydrogen-specific regulations are managed by different agencies. The Environmental Protection Agency and the Pipeline and Hazardous Materials Safety Administration, among other government agencies, manage regulatory regimes around production, emissions reporting, storage, transportation, delivery requirements, and import/export terminals. However, there are gaps when it comes to hydrogen use in power plants, commercial and residential heating, and rail and maritime vehicles, as well as blending limits with natural gas.[32] Further adoption of clear regulations is imperative for reducing risk for stakeholders and building out the hydrogen economy.

4. **Are there active public policy incentives for clean hydrogen?**

Political support for hydrogen continues to gather strength, with most government policies focused on producing low-carbon hydrogen. California, Germany, Japan, Norway, Switzerland, the EU, India, and Portugal have all announced policies to stimulate hydrogen demand using mandates, auctions, financial rewards, public procurement requirements, taxes, quotas, or contracts for differences (CfD). Most of these measures have not yet been enacted; however, their quick and widespread implementation could unlock more projects to scale up demand. Other countries, such as Greece and Finland, have unveiled national targets for new clean hydrogen production but still need to roll out financial incentives and other market development policies to advance the hydrogen market.[33,34]

5. **What public statements are available that indicate the interests, plans, or specific actions of the potential clean hydrogen market participants?**

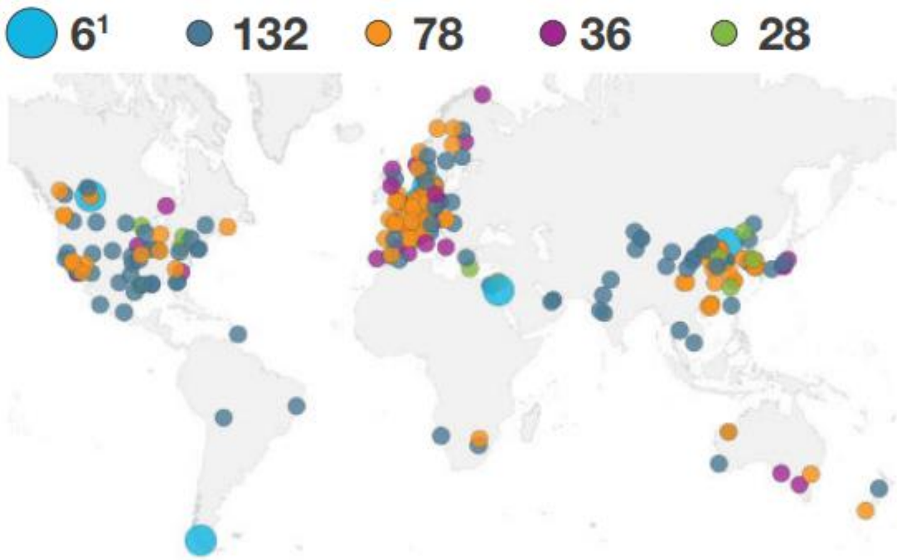
While official commitments from governments and industry on new hydrogen activities are crucial, in many cases there are signs of a region's broader interest in hydrogen. Such interest may come from a local government analysis, public comments from industry leaders on the potential value of hydrogen, or from strategic partnerships that signal the intent of stakeholders to support hydrogen. This type of market research is qualitative but can provide insights about demand-side interest in clean hydrogen and the potential headwinds and tailwinds of government and industry support of hydrogen.

6. **What are the plans to expand clean hydrogen use in the region, and is there announced interest from private capital to support development?**

Active and planned investments in hydrogen are the best indicators of a region's interest. For instance, more than 1,000 clean hydrogen projects are in development around the world, spanning readiness levels, from proof of concept to final investment decision (FID) and operational. Having projects that reached FID can signal that a region has the necessary ingredients for supporting a new clean hydrogen project. Most FID projects are in the United States, Canada, the EU, China, and Japan (Figure 7).[35] All of these projects are expected to result in 3 Mt/yr of clean hydrogen supply if they become operational.[36]

Figure 7.

Clean hydrogen projects: FID, under construction, or operational



There are about 280 clean hydrogen projects that have reached FID, are under construction, or are operational around the world, mostly in Europe, the United States, and Asia. These projects could bring more than 3 Mt/yr into the market when all become operational.[1] For multiphase projects, the first phase decides the project maturity. Source: See first figure mention in text for sources.

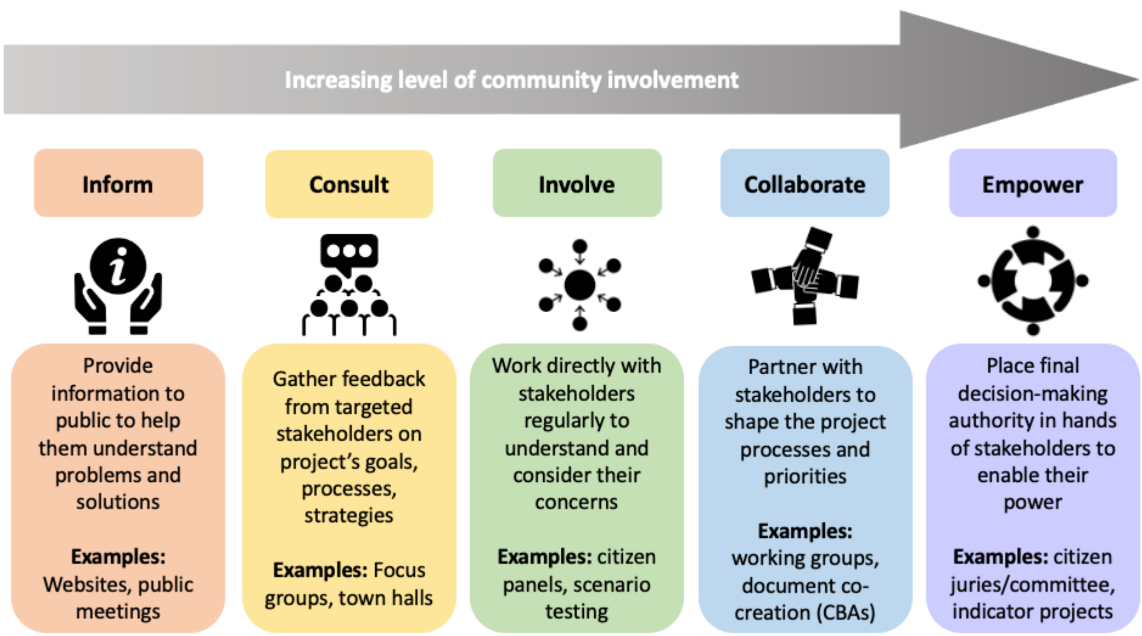
7. What are local communities' views on clean hydrogen?

Community support is fundamental for developing the clean hydrogen economy. Around the world, energy project developers increasingly have sought community engagement so they can bring value to communities and actively contribute to their well-being. The efforts have moved beyond outreach campaigns, in which communities are simply informed or consulted, to active engagement, when communities' concerns are heard and addressed and their collaboration affects project processes, priorities, and decision-making (Figure 8).[37,38]

While clean hydrogen adoption will reduce greenhouse gas emissions, local impacts on communities, such as nitrogen oxide emissions from hydrogen combustion, must be mitigated. Moreover, engaging with communities allows project developers to identify and address unforeseen impacts and help establish project priorities. Understanding communities' views and expectations about clean hydrogen projects and actively partnering with them will contribute to a project's success.

Figure 8.

Spectrum of community involvement in hydrogen projects



Clean hydrogen projects should pursue increasing involvement with communities to ensure project success.[e] *Adapted from: See first figure mention in text for sources.*

Untapped Growth Potential

The third layer of the framework evaluates potential resources in the region that could be leveraged for scaling hydrogen market development. Resources may include human capital, availability of energy sources and critical materials for hydrogen production, presence of geologic formations, and a technology development ecosystem.

1. **Are there energy and other input sources for clean hydrogen production?**

Hydrogen is an energy carrier that requires energy input for its production. Any energy source can be used to produce hydrogen, including fossil resources, renewable energy sources, and other energy carriers such as electricity. Hydrogen supply will depend on the availability of regional resources as well as environmental targets (carbon intensity) and social acceptance of production methods. Carbon capture and storage can be the most economical choice, but in some regions, there is social resistance to CO_2 storage. Water is an input to produce hydrogen via electrolysis, so its availability may affect production.

A region's energy production potential and availability of hydrogen production inputs strongly determine which hydrogen production feedstock will be chosen. For locations that do not have adequate hydrogen production inputs, developing an international supply chain will help. Cost-effective carrier and transport methods (i.e., using liquefied hydrogen or ammonia, or transportation via pipelines), trade agreements, and receiving transport infrastructure (e.g., port infrastructure) will shape the feasibility of international trade.

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[e] Community Benefit Agreements (CBAs) are signed by communities and developers to identify the benefits a developer agrees to deliver to a community in return for supporting the project. Source: U.S. Department of Energy Office of Minority Business & Economic Development, "Guide to Advancing Opportunities for Community Benefits through Energy Project Development," August 1, 2017. https://www.energy.gov/diversity/articles/community-benefit-agreement-cba-resource-guide

2. **What is the potential demand for clean hydrogen in end-use market sectors?**

Global hydrogen demand in 2021 was around 94 Mt, with almost all demand coming from refining and industrial uses, while demand for new applications remained low. More must be done to create demand in sectors such as transportation, power generation, heavy industry, and heating. A common way to determine potential applications for hydrogen is to look at end uses that are difficult to electrify. Hydrogen should be considered for use in heavy-duty vehicles, industrial heat, shipping and aviation, and high-power distributed systems, such as drayage.

Additionally, hydrogen has relevant applications in gas turbines and fuel cells for power generation; decarbonizing refining processes; and chemical, fertilizer, and steel manufacturing. It also could be used in commercial and residential heating applications. Hydrogen is well positioned to decarbonize major emitters and fill the gaps where electrification fails to meet net-zero goals. Given the high cost of hydrogen infrastructure, hubs are important for incentivizing demand where it is co-located with supply. As governments look to form more hubs, location selection will depend on the evolution of hydrogen production and demand. Many regions are looking to develop hubs in port areas where novel end-use applications like maritime shipping and heavy machinery (e.g., forklifts) are located. Port hubs will be particularly important for regions where global hydrogen trade is expected to contribute substantially to their market.

3. **To what extent can existing end-use assets be converted to clean hydrogen—either 100% or as blended with natural gas?**

The readiness of end-use assets for partial or full conversion to clean hydrogen is critical to determining a region's near-term hydrogen market growth potential. The pace and scale of adoption can be accelerated by leveraging existing end-use assets rather than building new ones, and the extent of adoption can be assessed through modeling exercises and experiments. For instance, major turbine manufacturers have evaluated their technologies to determine a general level of hydrogen readiness.[39]

The blending capabilities of natural gas networks and end-use appliances require detailed study, as is happening in the United States, Europe and the U.K., and Japan. The National Renewable Energy Laboratory found in an October 2022 study that hydrogen blending into natural gas networks may not be as simple as previously reported.[40]

Many projects worldwide are testing the viability of blending 1% to 100% of hydrogen in natural gas pipelines. The Testing Hydrogen Admixtures for Gas Appliances project in the EU is testing hydrogen embrittlement, or the corrosion of metallic pipelines. HyDeploy in the U.K. is testing 20% hydrogen blends with appliances and expanding supporting infrastructure like monitoring systems. Thus far, HyDeploy has found no safety concerns with 20% blends, although there are challenges across the globe related to cost-effectively blending hydrogen in existing networks that have different characteristics (i.e., different appliances, operating conditions, ages), and the long-term effects on networks are still largely unknown.[41] Detailed reviews of a region’s specific gas system materials, components, and operations (e.g., pump types and pressures) can affect gas-hydrogen blending.

4. **What is the feasibility of expanding the supply chain needed to support increased clean hydrogen supply? Are there particular challenges in either critical materials, manufacturing, or construction?**

While the hydrogen industry is relatively mature, it is highly specialized and limited in size and scope. A transition to using hydrogen as an energy carrier will put considerable demands on construction companies, raw materials (e.g., steel and cement), and manufacturing of electrolyzers, fuel cells, and hydrogen-ready pipes, among other key enablers. While this element focuses on the long-term perspective, there could be new clean hydrogen projects that stall in the near term because of the lack of a robust supply chain. Countries with strong manufacturing, industry, and hydrogen capabilities may be at a competitive advantage in both the near and long term because of direct access to these existing resources.

5. **What human and knowledge resources are needed to support clean hydrogen market development on the planned scale?**

Locations with robust capabilities to support a hydrogen workforce, or that have a strong culture of clean technology startups, can act as key enablers of a clean hydrogen market. Technical schools, innovation centers, innovative businesses, and other human and knowledge resources can help support the scalability of a hydrogen market. The U.S. Department of Energy (DOE) offers insights for careers in hydrogen and in the fuel cell industry.[42] High-quality jobs across research and development (R&D), engineering, manufacturing, operations and management, communications, training, and outreach also will be needed to scale the emerging clean hydrogen economy.

6. **How can the current workforce in fossil fuel and adjacent industries transition and contribute to developing the clean hydrogen industry?**

Many workers who are vulnerable to job loss in the energy transition have valuable skills. For instance, chemical engineers working in oil refineries have skills that apply to the production of clean fuels and hydrogen.[43] In the United States, coal mining, oil and gas extraction, pipeline transportation, natural gas distribution, petroleum and coal products manufacturing, as well as electric power generation, transmission, and distribution employ nearly 800,000 workers along the value chain, from wellhead drillers to communications specialists, who can contribute to the creation of a clean hydrogen market. Over 44% of the workforce in at-risk sectors is well suited to take on new jobs in hydrogen.[44] Investing in transitioning these workers to the clean hydrogen industry not only addresses concerns regarding a just energy transition but is also good business practice. Clean hydrogen project developers around the world should work with labor groups, technical colleges, on-the-job training programs, and local communities to identify at-risk jobs and plan for their transition to clean hydrogen jobs.

7. **What public and private sector support for innovation is available that either currently supports or has the potential to support RD&D and future deployment of clean hydrogen technologies?**

Innovation occurs throughout research, development, demonstration, and deployment (RDD&D). A region's RDD&D activities can signal the level and type of interest in clean hydrogen market formation. In the United States, for example, the federal government's Hydrogen Shot program is highly focused on lowering the cost of electrolysis and supports RDD&D funding to achieve that goal. Beyond government funding, venture capital (VC) support for deployment of hydrogen projects can contribute to further adoption. In the first quarter of 2022, VC deals in the space totaled $700 million and mostly focused on hydrogen production, signaling investor interest in this segment of the clean hydrogen value chain.[45] From 2020 to 2022, VC investment in clean hydrogen increased seventeen-fold, reaching $3 billion.[46] Such interest is an opportunity for clean hydrogen project developers.

Case Studies Using the Hydrogen Market Evaluation Framework

This section applies the Hydrogen Market Evaluation Framework to several regions and countries, including the United States, Canada, the EU, the U.K., Japan, and China, demonstrating how using open-source research can offer insights into a region's market formation potential. Table 1 highlights key metrics for hydrogen market formation in each of the case studies. Answers to each question of the framework are included in the Appendix.

Table 1.

Highlights of key metrics for hydrogen market formation in each of the case studies

Theme	United States	Canada	European Union	United Kingdom	Japan	China
Today's Hydrogen Industry						
Hydrogen production	11.4 Mt, mostly through SMR (natural gas)	3 Mt, mostly through steam methane reforming (SMR) of natural gas	8.6 Mt, mostly using natural gas and coal	<1 Mt, mostly using natural gas	2 Mt, around 50% from fossil gas reforming	33 Mt, 60% through coal gasification
Hydrogen pipelines	1,600 miles	91 miles	Almost 1,000 miles	25 miles	Minimal	62 miles
Regional Interest and Support						
Financial support	• Financial incentives (e.g., 45V production tax credit) • Federal funding (for hubs) • Loan Programs Office support	• Financial incentives (e.g., Clean Hydrogen Investment Tax Credit and Carbon Sequestration tax credits) • Federal funding (e.g., Clean Fuels Fund)	• Federal funding (e.g., H2Use and H2Tech) • CfD subsidy schemes (Germany's H2Global and EU Hydrogen Bank's pilot auction)	• Federal funding (e.g., Net-Zero Hydrogen Fund and CCUS Infrastructure Fund) • CfD subsidy scheme • UK Infrastructure Bank	• Federal funding (e.g., Green Innovation Fund) • GX Economy Transition Bonds • CfD subsidy scheme introduced	• Central government and provincial funding
Cost reduction targets	$2/kg by 2026; $1/kg by 2031				$3/kg by 2030, $2/kg by 2050	

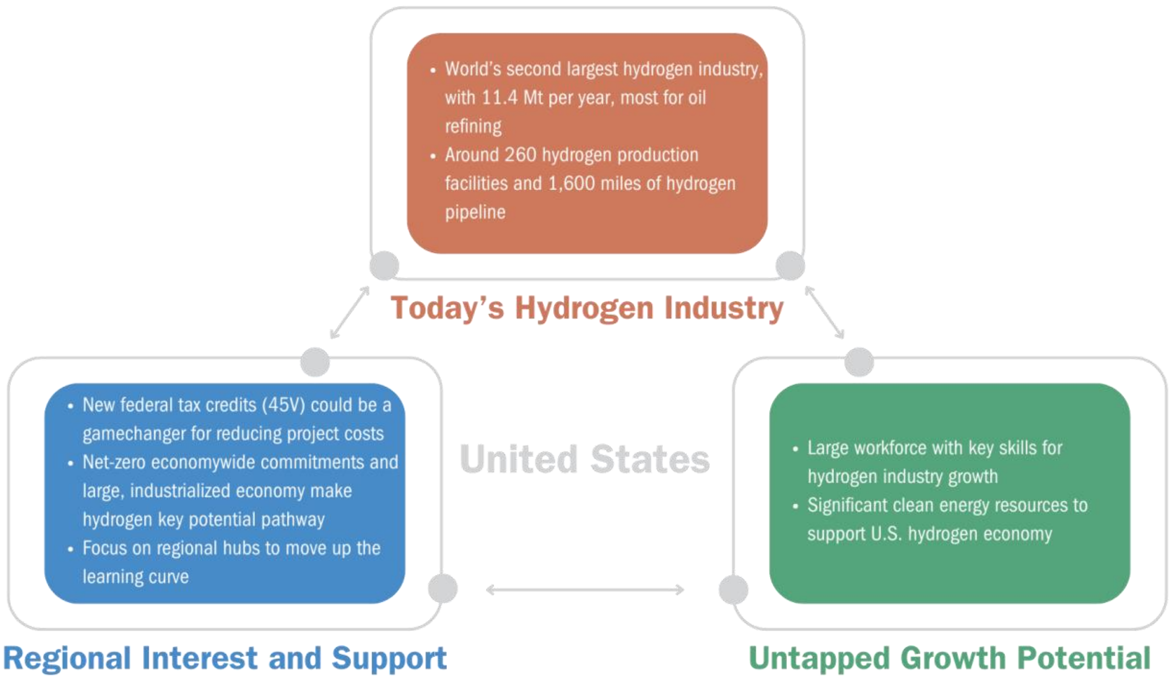
Focus on carbon intensity or production pathway?	Carbon intensity	Carbon intensity	Carbon intensity (Spain, Italy, and Portugal focus on green hydrogen production)	Carbon intensity	Targets focus on boosting all forms of hydrogen supply	National policy focuses on green hydrogen;[f] focus varies in subnational strategies
Untapped growth potential						
Renewable production pathway potential	Abundant renewable resources	Abundant renewable resources, water, and a low-carbon electricity grid	Abundant renewable resources in the Iberian Peninsula, offshore wind in the North Sea	Largest offshore wind industry globally	World leadership in solar PV production, and plans to expand nuclear fleet could enable future growth of green and pink hydrogen	Abundant wind and solar resources; electricity grid powered by 45% renewables, but mismatch of renewables and demand centers
CCUS production pathway potential	Considerable natural gas resources and CO_2 storage potential	Considerable natural gas resources and CO_2 storage potential	Abundant CO_2 storage potential in the North Sea	Abundant CO_2 storage potential in the North Sea		Important for reducing stranded asset risk for coal plants; most current hydrogen production near CO_2 storage
Key infrastructure plans	Regional Clean Hydrogen Hubs		European Hydrogen Backbone	North Sea Transition Deal	Building out international supply chain	
Future end-use sector focuses	Industrial sector (e.g., chemicals, steel, and refining), heavy-duty transportation, and long-duration energy storage	Long-range transportation, heating, industry, power generation	Broad end-use approach	Heavy industry, power, transportation, and particularly strong potential in the heating sector	Has prioritized uses in passenger vehicles and power generation	Focus on industry and heavy-duty transportation vehicles (buses and trucks)
Net importer or exporter?		Exporter	Importer	Exporter	Importer	

[f] Gray hydrogen is produced from steam methane reformation of natural gas without using carbon capture and storage technology to capture the CO_2 emitted from production. When CO_2 is captured, the resulting hydrogen is called blue. Green hydrogen is produced from electrolysis using renewable electricity (solar and wind). When nuclear electricity is used instead, it is called pink hydrogen.

United States

Summary: The United States is one of the most promising markets for clean hydrogen development (Figure 9). Its large industrial base, current hydrogen industry, and supportive policy environment align its national net-zero carbon targets with its clean hydrogen objectives. The recent federal tax credit (45V) for clean hydrogen production offers one of the largest government-backed financial incentives for clean hydrogen in the world. While progress is being made on encouraging energy end users to switch to clean hydrogen—for example, DOE is exploring ways to leverage approximately $1 billion to incentivize demand,[47]—questions remain about how to effectively sequence hydrogen market formation.

Figure 9.
U.S. Hydrogen Market Evaluation Framework summary



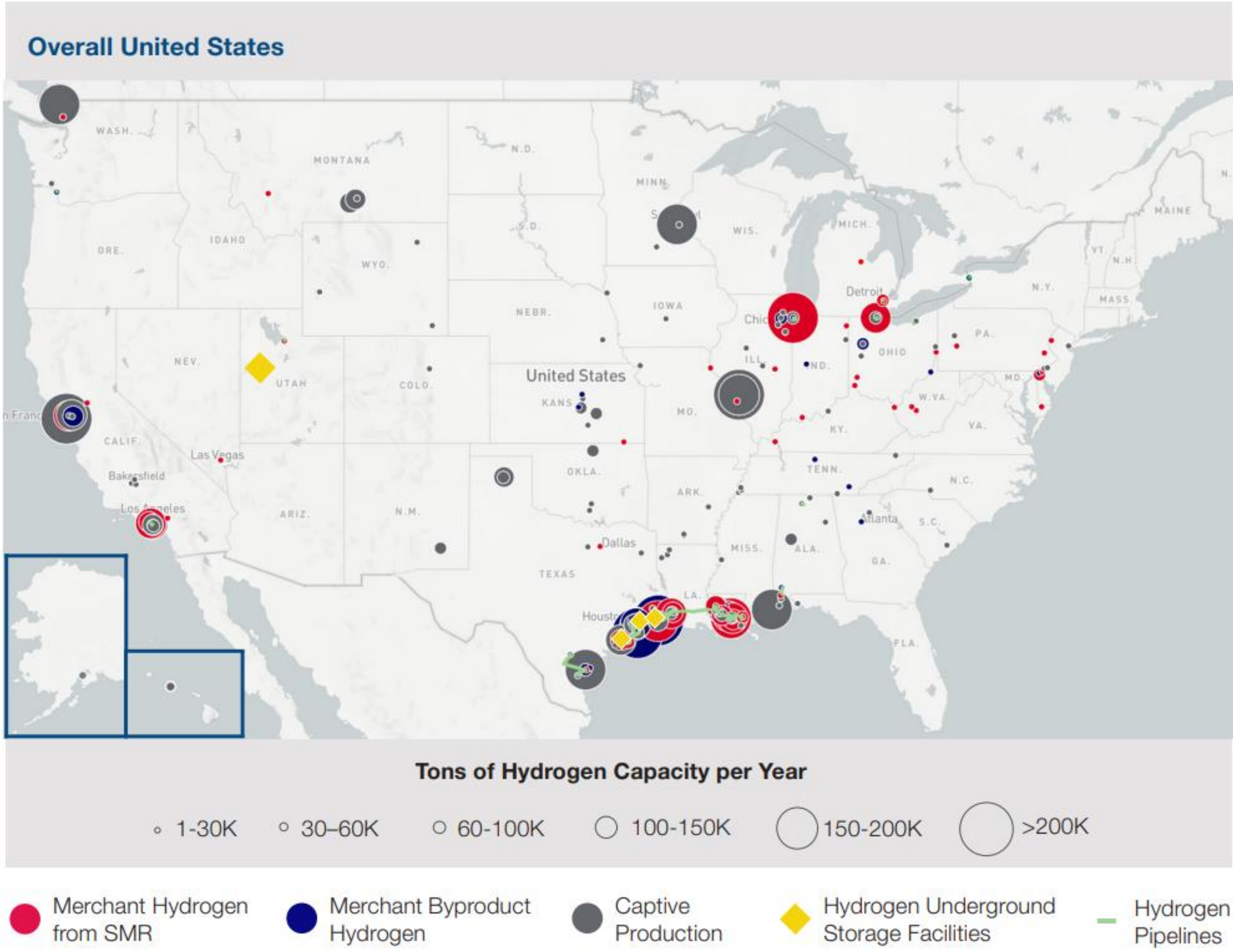
Today's Hydrogen Industry: The United States has one of the world's largest hydrogen industries. Hydrogen has been part of the U.S. economy for more than a century; the early U.S. natural gas system delivered manufactured gas containing more than 30% hydrogen.

In 2021, the United States produced roughly 11.4 Mt of hydrogen, more than 15% of the world's total.[48] Steam methane reforming (SMR) accounted for about three-quarters of total U.S. hydrogen production, while the remainder was produced as a byproduct of other industrial processes and usually consumed on-site. Fuel refining, ammonia, and methanol production account for roughly 90% of hydrogen demand in the United States, and other uses such as chemicals, transportation, metals, and fuels account for the remaining demand. U.S. hydrogen production emits about 100 Mt of greenhouse gases (GHG, tons of CO_2 equivalent) per year.[49]

As of 2021, there were roughly 260 dedicated hydrogen production facilities in the United States, located mostly in the Gulf Coast, throughout the Midwest, and in California (Figure 10).[50] There are 25 hydrogen pipelines in the United States, collectively spanning approximately 1,600 miles, and four underground hydrogen storage facilities in use or development—three of which are in the Gulf Coast.[51,52] The country's vast natural gas pipeline network could support small blends of hydrogen, though technical challenges affect understanding of this blending potential. Blends above 20% hydrogen, for instance, create operational issues in most natural gas pipelines today.[53] DOE is funding several research studies to evaluate pipeline suitability, necessary upgrades, and the safety of blending hydrogen into existing interstate pipelines, gas distribution systems, and gas turbine power plants.[54]

Figure 10.

Current U.S. hydrogen production by type



Hydrogen clusters near the Gulf Coast, in California, and in the industrial Midwest host most current hydrogen production. The Gulf Coast cluster has considerable resources to support production from multiple sources and storage and transport infrastructure. Source: See first figure mention in text for sources.

Regional Interest and Support: The United States has targets for reaching economywide net-zero emissions by 2050. At least two gigatons of emissions per year are coming from sources that are considered difficult to electrify, including aviation, shipping, trucking, heavy industry, agriculture, and aspects of the electricity system. As such, large-scale deployment of a low- or zero-carbon fuel will be necessary.

From 2021 to 2022, the U.S. Congress passed two of the most significant policy packages for hydrogen: the Infrastructure and Investment and Jobs Act (IIJA) and the Inflation Reduction Act (IRA). The IIJA included $8 billion for regional hydrogen hubs and an additional $1.5 billion for clean hydrogen research, development, and demonstration (RD&D) and electrolyzer manufacturing. DOE's Loan Programs Office is also supporting new clean hydrogen projects. DOE is leveraging roughly $1 billion of IIJA resources to foster development of demand-side mechanisms for the nascent clean hydrogen market.[55] The IRA introduced the hydrogen production tax credit, or 45V[g], which supports the formation of a clean hydrogen market from the supply side by decreasing clean hydrogen production costs according to the project's life cycle emission intensity.

DOE's *U.S. National Clean Hydrogen Strategy and Roadmap* was published in June 2023 and explores opportunities to deploy clean hydrogen across the economy to contribute to nationwide decarbonization goals. It establishes targets and three primary strategies to drive the growth of clean hydrogen adoption:

- Focus on difficult-to-decarbonize end-use sectors specifically in industry (chemicals, steelmaking, industrial heat), transportation (medium- and heavy-duty vehicles, maritime, aviation, rail), and the power sector (electricity generation, storage, stationary and backup power).
- Reduce the cost of clean hydrogen to $2 per kilogram (kg) by 2026 and $1/kg by 2031 (from the Hydrogen Shot initiative, which also focuses on transportation and storage infrastructure).
- Scale up regional hubs and benefit regional economies. Other DOE initiatives, including H2@Scale and Liftoff Strategy, support the Roadmap by providing additional resources and pathways to achieve goals such as cost reduction, the development of hydrogen hubs, decarbonization, and market formation.[56]

[g] 45V is the location of the Internal Revenue Service code section that details the tax incentive. The hydrogen production tax credit is usually referred to by this term.

The Pathways to Commercial Liftoff report on clean hydrogen says hydrogen adoption will take place in three phases until midcentury as incentives are rolled out, projects come on line, hydrogen costs decline, and adoption ramps up.[57] The *Hydrogen Strategy and Roadmap* aligns with the national long-term strategy to reach net-zero GHG emissions.[58] Specialized regional interests are emerging for clean hydrogen, shaped by existing resources and industries as well as policies. California, for example, has a series of supportive policies across the entire hydrogen production, delivery, and end-use domains.[59] To complement supply-side support in the Regional Clean Hydrogen Hubs (H2Hubs) program, DOE announced a notice of intent to implement a demand-side market support mechanism (i.e., auctions or contracts-for-differences schemes).[60] In addition, several recent Environmental Protection Agency (EPA) initiatives and regulations will help spur clean hydrogen demand, including the Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards, proposed carbon pollution standards for fossil fuel-fired plants, and the multibillion-dollar Clean Ports Initiative.[61]

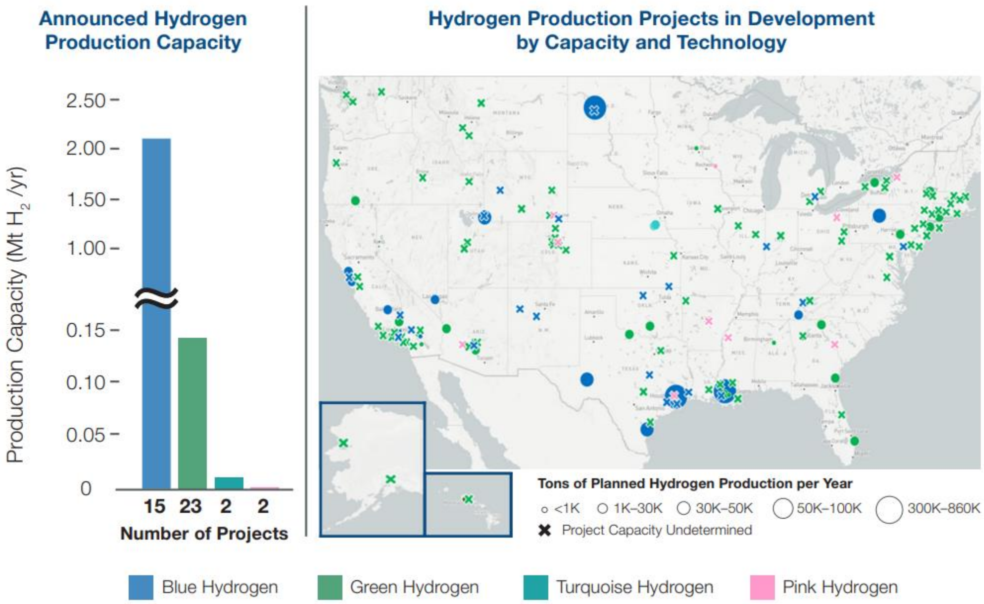
The United States has prioritized improving community engagement and the safe deployment of hydrogen as metrics for project success. The federal government created the Justice40 Initiative, which aims to spread the benefits from clean energy projects, including hydrogen, across communities by requiring that at least 40% of clean energy investments benefit disadvantaged communities.[62] Communities' views on hydrogen in the United States are affected by varying levels of knowledge, influence from interest groups, and historical factors.

Some views are influenced by safety considerations, which focus on hydrogen's high flammability and explosivity.[63] To address safety concerns, the EPA and the Pipeline and Hazardous Materials Safety Administration manage regulations around production, emissions reporting, storage, transportation, delivery requirements, and import/export terminals.[64] The recently announced Hydrogen Interagency Task Force will bring together agencies—including those related to production, delivery, storage, conversion, applications, H2Hubs, workforce, and equity and justice—in three working groups: (1) Supply and Demand at Scale; (2) Infrastructure, Siting, and Permitting; and (3) Analysis and Global Competitiveness.[65,66]

As of August 2022, there were 374 publicly announced projects that currently use, intend to use, or produce hydrogen in the United States, which would bring 2.2 Mt of clean hydrogen into the market.[67] The United States has over half of current and planned carbon capture capacity worldwide, and 85% of stationary emitting plants are within 100 kilometers of potential CO_2 storage sites.[h,68] Although blue hydrogen still represents the majority of capacity, projects producing hydrogen from renewables are popping up in regions like New England that did not previously host much production (Figure 11).[69] On-road mobility represents the end-use sector with the largest proportion of identified clean hydrogen activities, followed by electricity generation. Other announced project end uses for clean hydrogen include industrial heating, refining, and chemical applications.[70]

Figure 11.

Announced clean hydrogen projects across the U.S.



Over 2.2 Mt per year of clean hydrogen is expected from just 42 of the 177 announced production activities across the country (right). Most hydrogen production projects have not yet declared a capacity, but the scale and scope of certain undeclared projects suggests considerably more hydrogen will be added to the capacity already identified (left).

Many green hydrogen projects have been announced across the country, especially in New England, California, and near the Gulf Coast. Blue hydrogen projects will still hold the most capacity. Source: See first figure mention in text for sources.

[h] Stationary emitting plants: power and heat generation, chemicals, iron and steel, cement, fuel refining.

Untapped Growth Potential: Government support in the IIJA and IRA should help jump-start investment in decarbonizing the current U.S. hydrogen industry, while the Regional Clean Hydrogen Hubs program can help accelerate hydrogen adoption in new industries, such as heavy-duty trucking, steelmaking, and power generation. In places where hydrogen supply and demand are not co-located, investments in midstream infrastructure will also be important to support transportation and storage.[71] The United States maintains a sizable and skilled workforce that can transition to clean hydrogen, and there is bipartisan support for new clean hydrogen projects in most regions of the country. The U.S. government also is targeting significant RD&D resources toward lowering the cost of clean hydrogen production to $1/kg by 2030—a target known as the "Hydrogen Shot." This effort aims for clean hydrogen production of 10 Mt annually by 2030 (equal to current conventional hydrogen production), 20 Mt by 2040, and 50 Mt annually by 2050.[72]

The United States also maintains significant energy input resources to enable clean hydrogen production scaling. Natural gas and renewables accounted for 36% and 13%, respectively, of total primary energy production in 2022.[73] These sources could be tapped into for hydrogen production as their reserves are rich in the country. Nuclear electricity capacity is also abundant and can be used for clean hydrogen production. Regional differences of other key inputs such as water, waste resources, and CO_2 management systems (for blue hydrogen, for example) may affect hydrogen production in the future.[74]

DOE finds that hydrogen can decarbonize a wide range of U.S. sectors, particularly for use cases where decarbonization alternatives are costly or impractical (Figure 12).[75] Focusing on sectors where low-carbon hydrogen is a drop-in fuel should be a near-term priority, as should bringing down the cost of proton exchange membrane (PEM) electrolyzers.[76]

Figure 12.

Hydrogen is a large and growing U.S. market

Largest long-term H2 feedstock TAM

Sector	End-use	Role of H2 in decarb.	Description of switching costs	H2 feedstock TAM[1], $ billion 2030	2040	2050	H2 market size with full adoption[2], $ billion 2030	2040	2050
Industry	Ammonia		**Low:** Process currently uses fossil-based H2, hydrogen supply feed in place	4-10	4-11	5-12	4-10	4-11	5-12
	Refining		**Low:** Hydrogen supply feed in place	6-8			6-8		
	Steel		**Variable:** Highly dependent on current plant configuration and feedstock, may also include hydrogen distribution infrastructure		4-7	4-8	15-30	18-35	20-40
	Chemicals-methanol		**Variable:** Can limit switching costs by adding CCS to SMR, other approaches more costly with higher unit cost savings		2-6	3-7	5-12	5-12	6-14
Transport[1]	Road[3]		**High:** New vehicle power trains with fuel cells, refueling stations & distribution infrastructure	0	25-30	40-55	90-125	110-140	120-160
	Aviation fuels		**Moderate:** Fuel conversion / production facilities		5-15	10-30	8-20	10-25	10-30
	Maritime fuels[4]		**High:** New ship engines, port infrastructure & local storage, and fuel supply, storage, and bunkering infrastructure in ports	< 1	4-10	8-20	5-15	5-15	8-20
Heating	NG blending for building heat[5]		**Variable:** Will depend on pipeline material, age, and operations (e.g., pressure); requires testing for degradation and leakage	0	0	0	2-3	2-3	2-3
	Industrial heat		**Variable:** Dependent on extent of furnace retrofits required	0	1-3	2-5	7-10	7-10	7-10
Power	High-capacity Firm – 20% H2 (Combustion)[6]		**Moderate:** Retrofits to gas turbines, additional storage infrastructure	< 0.2	< 0.1	< 0.1	4-6	5-8	8-12
	Power – LDES[7]		**Moderate:** Retrofits to gas turbines, additional storage infrastructure	0	4-6	8-11	Varies based on cost-downs in other LDES technologies and composition of grid		

1 Represents the market size for clean hydrogen feedstocks in each end use; calculated by multiplying the clean hydrogen in the "Net zero 2050 – high RE" scenario by range of willingness to pay by end use reported in the DOE National Hydrogen Strategy and Roadmap; dispensing costs are subtracted from the road transport TAM and market size with full adoption
2 Represents the maximum market size if the hydrogen-based solution had 100% share of each end use
3 H2 feedstock TAM uses H2 demand from the DOE National Hydrogen Strategy and Roadmap assuming both medium- and heavy-duty trucks; H2 market size with full adoption is based on energy usage from Class 8 long-haul and regional trucks, which represent the significant majority of all medium- and heavy-duty truck energy consumption
4 Maritime fuel demand and split between ammonia and methanol maritime fuel from the Mission Possible Project report "A Strategy for the Transition to Zero-Emission Shipping", assuming U.S. ports use 6% of global maritime fuel based on volume of fuel used in global ports
5 H2 TAM based on DOE National Hydrogen Strategy and Roadmap assumption that all hydrogen for heating is used for industrial heat; H2 market size with full adoption assumes 20% hydrogen blending by volume
6 Willingness to pay is based on high-capacity factor firm combustion
7 Long Duration Energy Storage (LDES) hydrogen demand and willingness to pay from DOE National Hydrogen Strategy and Roadmap

Stakeholders identified the cost of hydrogen as the largest barrier to adoption, followed by a lack of supporting infrastructure. Source: See first figure mention in text for sources.

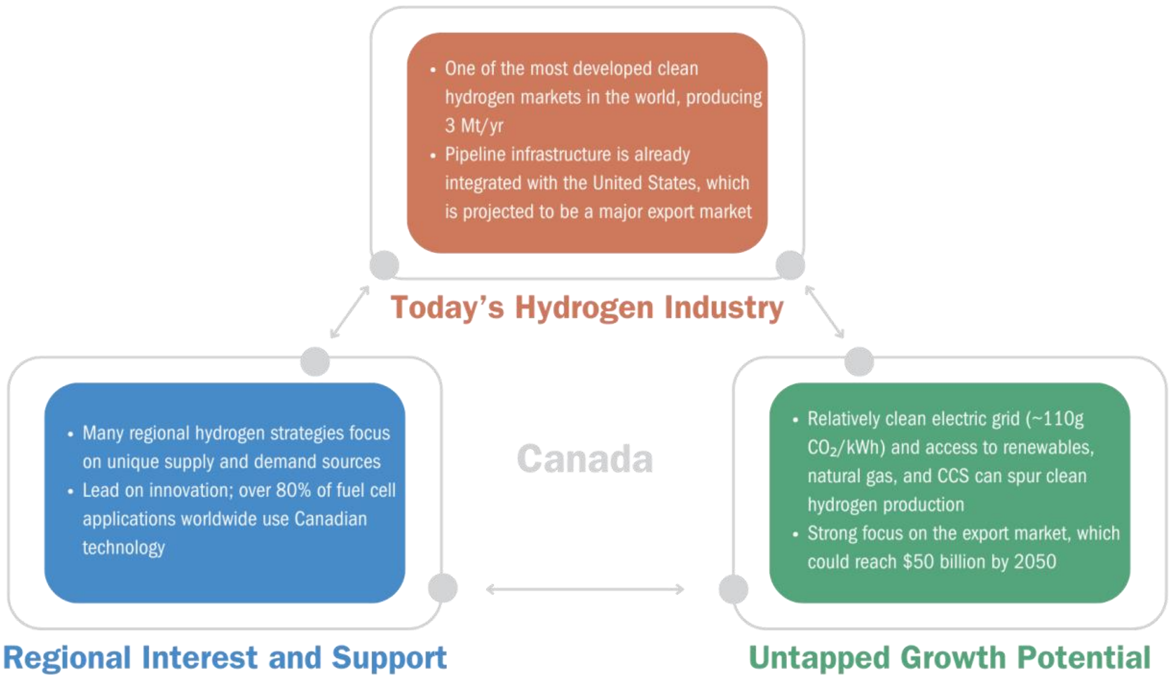
The United States has the workforce and research capabilities to support the hydrogen industry and aid in the clean energy transition. EFI Foundation research has identified that over 44% of the workforce in at-risk sectors such as coal mining, oil and gas extraction, pipeline transportation, natural gas distribution, petroleum and coal products manufacturing, as well as electric power generation, transmission, and distribution are well suited to take on new jobs in the clean hydrogen industry.[77] The United States also has many universities, colleges, and research institutions that can support clean hydrogen development. For instance, the 17 DOE national laboratories and 1,040 technical, trade, and community colleges with student populations greater than 1,000 and with at least one sciences program could support this.[78]

The public and private sectors in the United States are supporting the rapid development of clean hydrogen across the value chain to gain global leadership. The federal government's Hydrogen Shot program is focused on lowering the cost of electrolysis and supports RD&D funding to achieve that goal. DOE has dedicated IIJA funding to develop a supply chain for electrolyzers and fuel cells, focusing on production, manufacturing, and recycling.[79,80] In total, $500 million is earmarked for the development of manufacturing and recycling of clean hydrogen, and $1 billion is earmarked for electrolyzer development in fiscal years 2022 through 2026. Four of the "Global Top 20 Hydrogen Electrolyzer Manufacturers" in 2023 are located in the United States, according to Blackridge Research & Consulting.[81] VC interest also is rising.[82] For instance, Oregon-based Intersect Power plans to expand into green hydrogen production and raised $750 million in growth equity in 2022, making it the largest hydrogen private equity deal that year, according to PitchBook data.[83]

Canada

Summary: While Canada is only a modest hydrogen market today (producing roughly 3 Mt/year), it is still one of the world's largest producers of clean hydrogen. Abundant renewable natural resources will enable Canada to maintain this position, as will a focus on the export market to Europe and the United States. Canada already has established itself as a leader in hydrogen and fuel cell technology, and the importance of the country's energy sector to its economy gives it the expertise and infrastructure to develop a strong hydrogen market (Figure 13).

Figure 13.
Canada Hydrogen Market Evaluation Framework summary



Today's Hydrogen Industry: Canada is one of the top 10 hydrogen producers in the world today, producing about 3 Mt per year.[84] Roughly 80% of hydrogen in Canada is produced via SMR of natural gas without carbon capture and storage (CCS), and 0.3 Mt is produced from SMR with CCS, in which emissions from hydrogen production are captured and stored.[85,86,87] This makes Canada one of the most developed clean hydrogen markets in the world.

Western Canada is the country's leading hydrogen producer, followed by central, then Atlantic Canada.[88] Alberta, in western Canada, produces 2.4 Mt of hydrogen (80% of Canada's production);[89] British Columbia, Ontario, and Quebec have also emerged as leaders in the hydrogen industry.[90] Alberta alone has around 60 miles of hydrogen pipelines, and a gas company already has used existing infrastructure to blend 3% hydrogen with renewable energy to deliver fuel for more than 2,000 customers.[91,92] In total, Canada has 91 miles of hydrogen pipelines, although its extensive oil and gas pipeline infrastructure could be an asset in the future hydrogen industry.[93,94] Additionally, Canada's oil and gas pipeline infrastructure is highly integrated with the United States', which is projected to be an export market. Seven provinces are connected to the U.S. pipeline network.[95,96]

Canada is home to the world's largest PEM electrolyzer, which came on line in 2021 in Quebec. This unit has a capacity of 20 megawatts (MW) and produces 8.2 metric tons of hydrogen per day.[97] A 90 MW PEM electrolyzer is being built in Quebec to produce clean hydrogen and oxygen in a waste-to-methanol facility at a biorefinery. The facility is under construction and expected to be operational in 2025. It will produce 9.1 metric tons of hydrogen per day.[98]

Regional Interest and Support: Like the United States, Canada plans for hydrogen to play an important role in reaching the national net-zero emissions target by 2050.[99,100] In 2020, Canada released its national hydrogen strategy, which identifies opportunities for the industry and a plan for developing it in the near, medium, and long term. The strategy shows that hydrogen could contribute up to 30% of Canada's energy end-use needs by midcentury while delivering other benefits such as economic growth and job creation.[101] Generally, the Canadian government is focusing on low-carbon rather than renewable hydrogen; the government is aiming to drive down the carbon intensity of hydrogen production over time.[102]

Many regional governments have their own hydrogen strategies to focus on supply and demand sources (e.g. the *B.C. Hydrogen Strategy*, *Alberta Hydrogen Roadmap*, *Ontario's Low-Carbon Hydrogen Strategy*, and *2030 Quebec Green Hydrogen and Bioenergy Strategy*).[103] British Columbia, for example, is focusing on utilizing its extensive renewable resource base to scale clean hydrogen production.[104] Additionally, most regions have decarbonization standards and policies that may support investments in hydrogen. For example, British Columbia has its own Low Carbon Fuel Standard; the CleanBC Industry Fund supports GHG emissions reductions projects for large emitters; and the CleanBC Go EV Program supports the construction of hydrogen refueling stations (HRS).[105]

Box 1

Canada's hydrogen project development pipeline

Several clean hydrogen projects are in early development stages. Many are focused on clean hydrogen and ammonia production from onshore wind or electricity from the grid, which is over 80% renewable in the eastern region. The domestic and export markets to Europe are the main demand driver.[106,107] In Nova Scotia, a $6 billion project will produce green hydrogen and clean ammonia, starting operation in 2025. Initially, the development will be powered by power purchase agreements, but a 2 gigawatt wind farm will be built in 2026, when production is expected to reach 1.1 Mt per year. The project already secured two offtakers.[108] A hydrogen hub in Manitoba and a hydrogen plant with carbon capture technology in Alberta are also in early development stages.[109] In Ontario, the Niagara Hydrogen Centre will use a 20 MW electrolyzer to produce green hydrogen; the provincial government supports the project with a tax exemption from 2024 to 2033 for electricity generated for hydrogen production.[110]

Canada's proposed Clean Hydrogen Investment Tax Credit could be important for driving low-carbon hydrogen production.[111] The $17.7 billion program would be available between 2023 and 2035, supporting 15% to 40% of eligible project cost based on life cycle carbon intensity of hydrogen production and the facility's ability to meet certain labor requirements. Projects with emissions intensity less than 0.75 kg CO_2e/kg H_2 could apply the credits to 40% of eligible project costs, while projects with emissions of 0.75 kg to 2.0 kg CO_2e/kg H_2 could claim 25%. Projects with emissions intensity of 2.0 kg to 4.0 kg CO_2e/kg H_2 could claim 15%.[112] The federal government also awards tax credits for up to 60% of CCUS projects to support the low-carbon transition.[113]

Canada has other national policies and resources dedicated to economywide decarbonization that may support clean hydrogen's development. For example:

- The national requirement for 100% of new cars sold to be zero-emissions by 2035; includes electric vehicles (EVs), fuel cell electric vehicles (FCEVs), and plug-in hybrid electric vehicles (PHEVs).
- The new Federal Clean Fuel Standard requires liquid fossil fuel suppliers to gradually decrease emissions from 2023 to 2030 and, following California's model, creates a credit market for trading lower-carbon fuel.[114,115]
- The Clean Fuels Fund will receive $1.5 billion over five years to help lower the upfront investment cost for new clean fuel production capacity. Although

investments will encompass multiple types of fuel, the fund requires that at least 10 hydrogen projects be supported.

- The Zero Emission Transit Fund invests in low-emissions public transit, school buses, and accompanying infrastructure.[116] These transportation-focused policies will help Canada reach its deployment goal of 50,000 FCEVs by 2030 (in the Announced Pledges Scenario[i]).[117] There are other funds and initiatives like the Net Zero Accelerator, which provides roughly $6 billion for projects that reduce emissions.[118]
- The Canadian government recently pledged nearly $19 million over five years to develop codes and standards to support the hydrogen strategy to address these regional differences.[119,120]

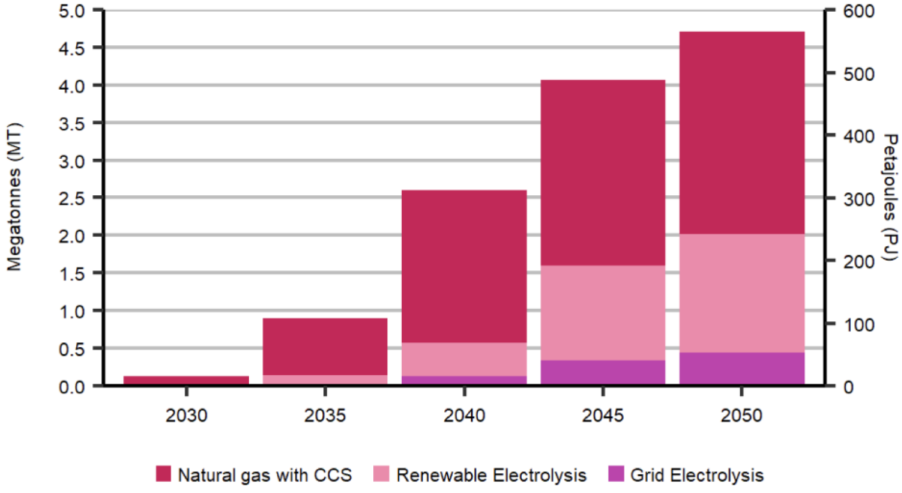
Canada's hydrogen strategy outlines engagement with indigenous communities as a priority, and the government is actively exploring ways for indigenous communities to become leaders within the hydrogen industry. The energy sector is already one of the most important sectors for indigenous groups, and these communities have significant expertise and resources.[121] Hydrogen applications have the potential to provide additional benefits to these groups; FCEVs could be important for communities in colder regions where batteries have short life spans.[122]

Untapped Growth Potential: Canada anticipates that hydrogen could make up 30% of the nation's energy mix by 2050.[123] Because of the many hydrogen production pathways, all regions can participate, spurring interest in the hydrogen economy across the nation.[124] By 2050, the Canada Energy Regulator anticipates hydrogen demand growth of at least 4.7 Mt, with over half of the supply coming from CCUS-enabled projects (Figure 14).[125]

[i] Canada's Announced Pledges Scenario is the IEA's model for Canada to reach its net-zero commitments and targets.

Figure 14.

Hydrogen production by technology

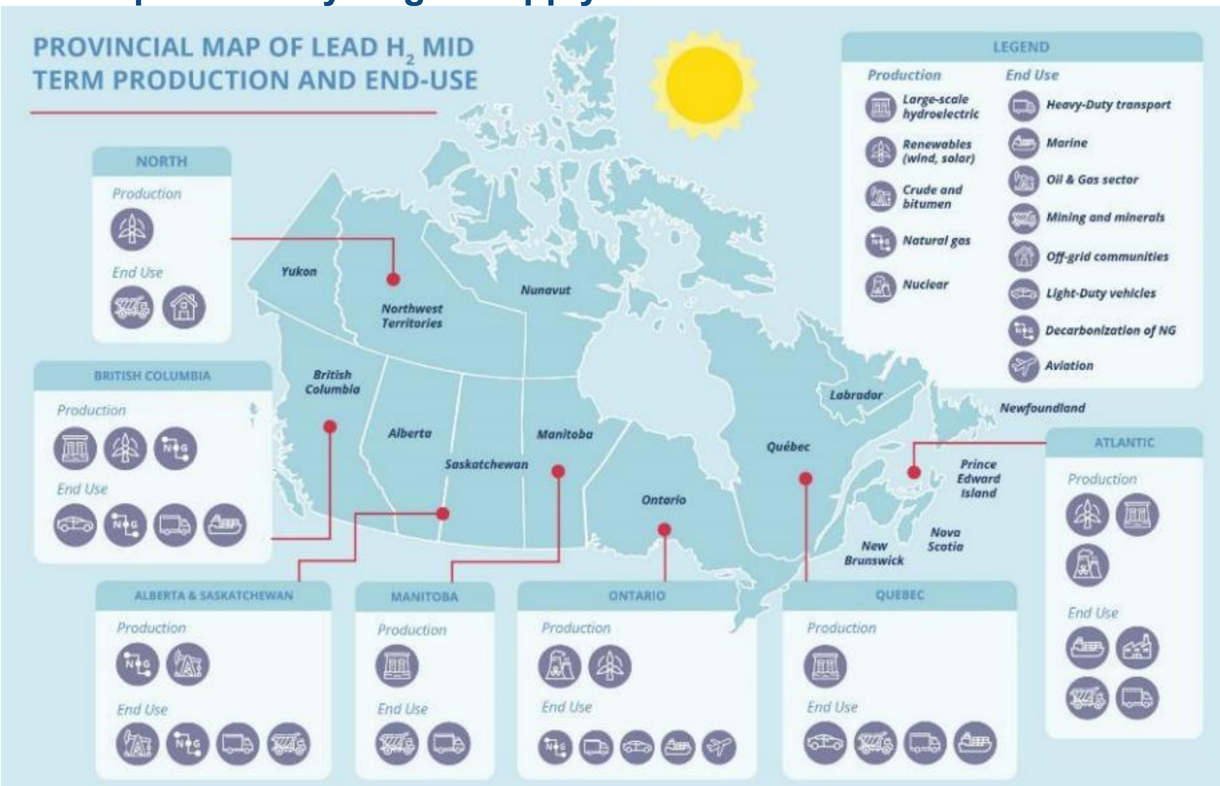


By 2050, hydrogen produced from fossil fuels integrated with CCS is expected to make up 57% of total production, with electrolysis (mostly from renewables) making up the rest of the supply. Source: See first figure mention in text for sources.

Canada has abundant CO_2 storage potential and is rich in feedstocks to produce low-carbon hydrogen, such as hydroelectricity and nuclear generation[j], large natural gas resources, a large-scale biomass supply, and freshwater resources.[126] The large share of Canada's electricity grid powered by renewable resources (almost 70%) is important for converting natural resources to hydrogen without heavy emissions.[127] As seen in Figure 15, British Columbia, Manitoba, Ontario, Quebec, Labrador, and Prince Edward Island have the largest potential for hydrogen production from renewable sources.[128] Notably, Ontario (with 75% of the nation's nuclear plants) and New Brunswick host the only opportunities for hydrogen production from nuclear. Integrating hydrogen into the grid also will play an important role in storing excess electricity and producing green hydrogen as intermittent renewable-based energy sources contribute to more electricity generation.[129]

[j] Nuclear and hydropower are both considered renewable in Canada.

Figure 15.
Canada's potential hydrogen supply and demand sources



Map of potential clean hydrogen production and end-use resources. Regional hubs will develop hydrogen economies based around their particular resources. Source: See first figure mention in text for sources.

The carbon intensity and cost of CCUS versus renewable-based production will largely determine relative uptake. The nation has many CCUS projects and has the second most suitable geology for CO_2 storage worldwide. Canada is also the world's fourth-largest producer of natural gas.[130,131]

Canada is encouraging the early deployment of hubs, which will give all regions the opportunity to benefit from their particular mix of production based on local resources and economic factors. Many hubs have formed within industrial clusters to support demand from oil refineries and chemical plants. Provincial policies, infrastructure, resources for production, and end-use applications are driving the current development.[132, 133]

Western Canada has supported the growth of hubs with its feedstock supply, infrastructure, government support, and capacity for CCUS to support many forms of hydrogen.[134] The hydrogen strategy additionally focuses on the potential to develop hubs in port areas to encourage multiple end-use applications, mostly in hydrogen fuel cell equipment. Hubs are also proposed along the transport corridor between Montreal and Detroit to connect supply and demand from multiple sources, such as manufacturing and transportation.[135]

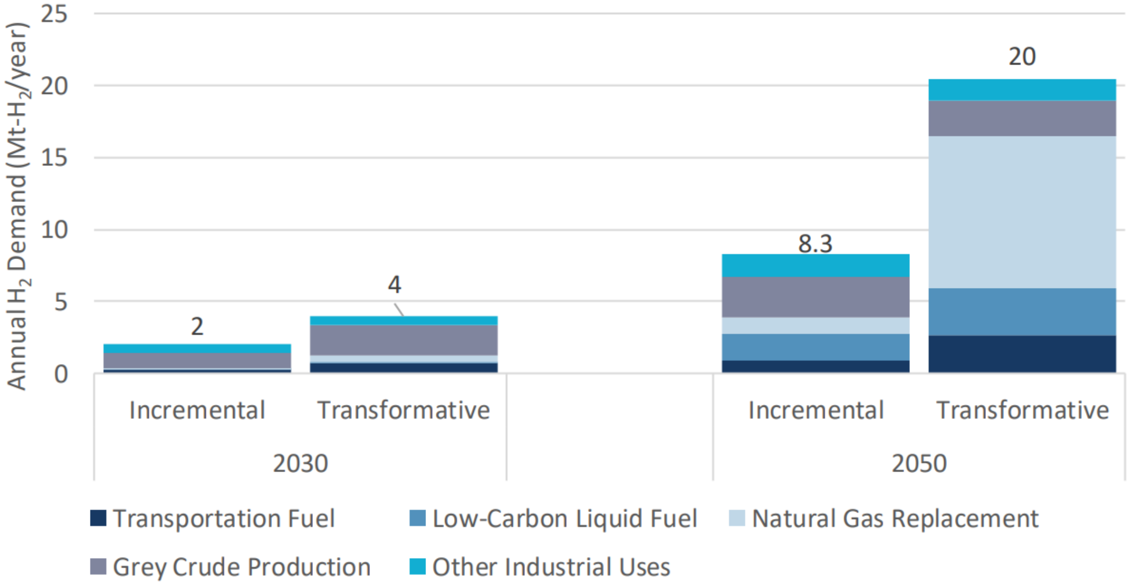
Canada is well positioned to become a top global clean hydrogen producer. According to the government, the export market for clean hydrogen and related technologies could double the economic potential of Canada's hydrogen industry by 2050.[136] For example, California currently receives about 50% of Canada's gas exports to the United States, and this relationship could form the basis of future hydrogen sales.[137] Canada is also working on agreements with other locations where demand will outstrip supply to export excess hydrogen production. Focuses are the United States, the EU, and parts of Asia including China and Japan.[138] Notably, the Canada-Germany Hydrogen Alliance establishes that the two countries will work to coordinate standards and develop supply chains, and Canada will supply Germany with clean hydrogen by 2025.[139] Canada is also focusing on integrating Europe's CertifHy green and international definitions of low-carbon hydrogen as part of its investment strategy.[140]

Canada takes a cross-sectoral approach to hydrogen demand. By 2030, the country aims to produce 4 Mt of hydrogen to meet 6% of the nation's energy demand. By 2050, hydrogen could deliver up to 30% (20 Mt) of Canada's end-use energy across sectors, including long-range transportation, power generation, residential and commercial heating, and as an industrial feedstock.[141] In the near term, demand for hydrogen in oil refineries will dominate uptake. Canada is also pursuing hydrogen projects that seek to decarbonize steelmaking and ironmaking; Quebec is already home to a clean hydrogen-powered steelmaking facility.[142]

Hydrogen can replace diesel as a fuel, reducing emissions in areas like the mining sector and the heavy-duty freight industry.[143] Although FCEVs remain more expensive than EVs, fuel cell applications, particularly in heavy-duty trucks, have several advantages over electric batteries.[k] Acquiring the upfront capital to build out hydrogen refueling infrastructure and reducing the production cost of FCEVs by achieving economies of scale will be important for demand growth.[144] The viability of using hydrogen as a natural gas replacement in heating sectors or for power production is still being researched, but it could be a large driver of domestic demand in the long run (Figure 16).[145,146] Replacing natural gas with hydrogen for residential heating could be important in colder regions where heat pumps do not fare as well.[147] A pilot project in Alberta is expanding previous efforts and is testing the feasibility of blending hydrogen into natural gas networks to deliver heat to about 5,000 homes and buildings, starting with roughly 5% blends.[148]

Figure 16.

Expected demand for end-use hydrogen applications under incremental and transformative scenarios in 2030 and 2050



By 2030, demand for hydrogen for gray crude production (refining) and other industrial uses is expected to dominate, although, under a more ambitious scenario, transportation fuel and use as a natural gas replacement also will play a role. By 2050, use of hydrogen increases as a natural gas replacement (in power generation—either in hydrogen-powered gas turbines or blended into natural gas pipelines—or in heating). Under the transformative scenario, hydrogen could make up 20 Mt (31%) of delivered energy to help Canada reach net-zero goals (under the incremental scenario, Canada would not reach net zero). Source: See first figure mention in text for sources.

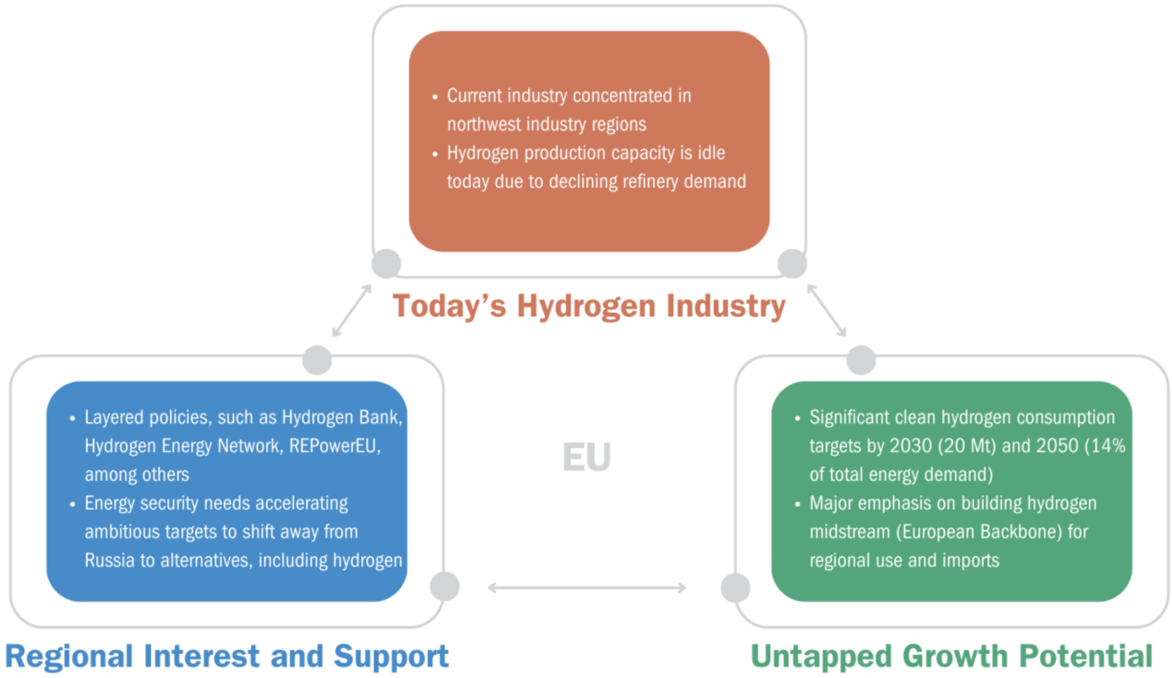
[k] Long recharge times, HRS requirements, a lack of storage capacity, and poor performance in colder regions make batteries less promising than hydrogen in Canada.

The Canadian government has prioritized RD&D, and national and international collaboration is core to its strategy. Canada leads in hydrogen technology innovation and is a global leader in intellectual property.[149] Over 80% of fuel cell applications worldwide use Canadian fuel cell technology; the fuel cell system used to create the first hydrogen-powered train in Germany was supplied by and is the intellectual property of a Canadian company.[150,151] Many universities have their own hydrogen research centers, including the University of Saskatchewan, where a project is underway to develop a catalyst to convert any feedstock into clean hydrogen.[152] The Canadian government is funding much of this research, including the hydrogen pillar of National Research Council Canada's Advanced Clean Energy program. The nonprofit Alberta Motor Transport Association is leading a collaboration to transform all trucks within the province to net-zero emissions, working with multiple private companies to test heavy-duty trucks powered by hydrogen. This demonstration project has many funding sources including the federal government, Emissions Reduction Alberta, and the private sector.[153,154]

European Union

Summary: Europe is seen by investors as one of the most promising hydrogen market regions.[155] The European Commission created a layered policy approach to clean hydrogen project development, with support for supply-side activities (mostly for green hydrogen), hydrogen infrastructure, and incentives for consumers. As a result, Europe is home to the largest share (30%) of new proposed hydrogen investments globally, driven by strong government support.[156] The region's interest in hydrogen primarily centers on decarbonization and energy security goals, especially because of Russia's invasion of Ukraine and the resulting energy crisis. Europeans see shifting to clean hydrogen as a way to reduce their dependence on fossil fuels, especially Russian imports. Many countries, including Germany, France, the Netherlands, Spain, and Portugal, have their own national strategies and targets, mostly aligned with the EU's priority of green hydrogen among other production options (Figure 17).

Figure 17.
EU Hydrogen Market Evaluation Framework summary



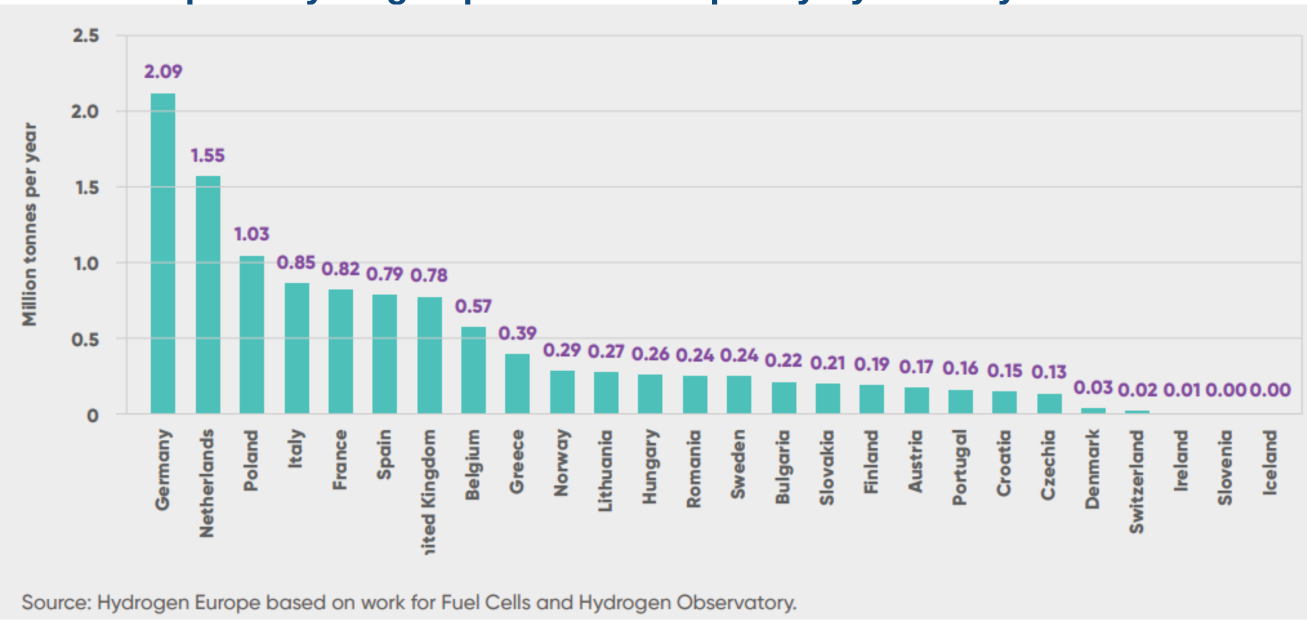
Today's Hydrogen Industry: Europe has one of the world's largest hydrogen industries, concentrated in its highly industrialized regions. Europe produces and consumes around 8.6 Mt of hydrogen per year and maintains a production capacity of around 11.5 Mt/yr across 504 facilities.[157] Hydrogen represented 2% of the EU energy mix, with 96% of the supply coming from natural gas and some from coal, resulting in the release of 70 Mt to 100 Mt of CO_2 annually.[158,159] While Europe has a sizable new project pipeline, low-carbon hydrogen production remains very small; in 2020, the installed capacity of blue and green hydrogen projects totaled 74 metric tons per day.[160] Europe has almost 1,000 miles of hydrogen pipelines to connect supply and demand; 95% are located in Northwest Europe.[161,162]

Petroleum refining accounted for over half of the EU's hydrogen consumption in 2020, followed by ammonia at 29%, other chemicals at 7%, methanol at 4%, energy at 4%, and other uses at 5%.[163] According to one study, Europe is the only refining region that has not recovered to pre-pandemic demand levels; as a result, a decrease in refining capacity is expected over the coming years.[164]

Northwest Europe makes up 57% of the EU's hydrogen demand and around 5% of global demand.[l] Germany is Europe's largest hydrogen user and maintains over 2 Mt/yr of production capacity. Other countries with large hydrogen production capacities include the Netherlands (1.55 Mt/yr), Poland (1.03 Mt/yr), Italy (0.85 Mt/yr), and France (0.82 Mt/yr) (see Figure 18).[165,166]

Figure 18.

Total European hydrogen production capacity by country



Germany and the Netherlands lead production capacity in Europe (based on 2020 data). Source: See first figure mention in text for sources.

There is a relatively small market for merchant hydrogen sales in Europe; roughly 80% of production is consumed by the same entity on-site.[167] There are at least three SMR units with some carbon capture, representing around 0.5%, or 56 kilotons (kt) per year, of the region's total hydrogen production capacity. As of 2022, there were around 143 power-to-hydrogen projects operating in Europe, accounting for 0.25% of total installed capacity, or 29 kt/yr. While some of these are demonstration projects, most are very small-scale facilities

[l] The northwestern region of Europe encompasses Belgium, Denmark, France, Germany, the Netherlands, Norway, and the U.K.

designed to co-locate supply with demand at glass manufacturers, food processing plants, and locations with specific cooling needs.[168]

The EU's Energy Communities Repository is an initiative to help local communities engage with energy projects for their benefit, and the Rural Energy Communities Advisory Hub provides further assistance to rural communities.[169] A study in Germany and the Netherlands showed public knowledge about hydrogen remains low, and there are few projects engaging the public. In Germany, social acceptance is harmed by a distrust of industry, and there are questions regarding whether hydrogen projects will benefit communities.[170]

Regional Interest and Support: The EU's strategy sees hydrogen as a key to a future integrated energy system, alongside "more efficient and circular [resources]."[171] Moreover, the region's plans see large-scale deployment of hydrogen as necessary for achieving near-term decarbonization targets of roughly 50% emissions reductions economywide by 2030. Europe is offering layers of policy support, mostly for green hydrogen, with an overall target of producing 10 Mt/yr and importing another 10 Mt/yr of renewable hydrogen by 2030 (with 4 Mt/yr from ammonia and its derivatives).[172] These layers of policy support are discussed below.

- The first phase (2020 to 2024) of the EU's hydrogen strategy aims to produce 1 Mt/yr of renewable hydrogen via 6 gigawatts (GW) of new electrolysis. In a second phase (2025 to 2030), Europe plans on installing 40 GW of electrolysis with production capacity of 10 Mt/yr.[173] *A Hydrogen Strategy for a Climate-Neutral Europe* (August 2020) provides a policy framework within which the European Clean Hydrogen Alliance will develop an investment agenda and a pipeline of concrete projects. It complements the Strategy for Energy System Integration, which describes how the ongoing workstreams of EU energy policy, including hydrogen development, will foster an integrated energy system that is climate-neutral (i.e., it offsets the same amount of GHG that it emits) with renewable electricity, circularity, and renewable and low-carbon fuels at its core.[174]

- In addition to ambitions to achieve carbon neutrality by 2050, Europe's Fit for 55 legislative package (2021) targets 55% reduction of GHG emissions by 2035. To achieve this goal, the Hydrogen and Decarbonized Gas Market Package was created to improve hydrogen infrastructure and create an efficient market. Its supporting materials include new standards and certifications (e.g., it allows for blending with up to 5% hydrogen, access to LNG terminals, and gas storage for low-carbon gases), as well as knowledge sharing resources including the establishment of the European Network of Network Operators for Hydrogen.[175]
- The Important Projects of Common European Interest program's H2Use and Hy2Tech put billions of dollars of support into projects by a range of stakeholders that improve the hydrogen value chain, including the technological development of electrolyzers, infrastructure, and hydrogen applications in the industrial and mobility sector.[176] To generate demand within the industry and transport sectors, legislation such as the Renewable Energy Directive revision, the REFuelEU Aviation, FuelEU Maritime, and the Alternative Fuel Infrastructure Regulation have been put in place.[177]
- In the context of Russia's invasion of Ukraine, the REPowerEU plan seeks to end fossil fuel imports from Russia by 2030 and speed up renewable deployment. This plan puts $27 billion in investments toward hydrogen infrastructure to enable the transition and strengthens the European Union Innovation Fund's contributions toward developing the hydrogen economy.[178]
- To complement the REPowerEU plan, the Hydrogen Accelerator initiative sets production targets of 10 Mt of renewable hydrogen and the import of 10 Mt of hydrogen (including 6 Mt of renewable hydrogen) by 2030. To support the Hydrogen Accelerator, the EU has proposed the creation of the European

Hydrogen Bank to help unlock investments in clean hydrogen through an auction-based model. In fall 2023, a pilot auction took place with $800 million dedicated to support renewable hydrogen production.[179] Considering the REPowerEU plan, European manufacturers targeted 25 GW of total annual electrolyzer production capacity by 2025.[180] The EU CertifiHy certification system will be used to verify that emissions comply with regulations. The REPowerEU plan also includes funding for the Clean Hydrogen Partnership, which is collecting research on best practices from around the world to develop hydrogen hubs ("hydrogen valleys").[181] Knowledge sharing and hub buildout have been first priorities since the Fuel Cells and Hydrogen Joint Undertaking in 2015.[182]

Box 2

National hydrogen strategies across the EU

Sixteen countries within the EU have formulated their own national hydrogen strategies. Among them:[183]

- **Germany's** "National Hydrogen Strategy" was created in June 2020 to support the country's ambitious plans to reach carbon neutrality by 2045.[184] The strategy was updated in July 2023, leading to a doubling of Germany's electrolysis capacity to "at least" 10 GW by 2030 and allowing blue hydrogen pathways for the first time. Additionally, funds will be available for 1,100 miles of new hydrogen pipelines. The German plan also makes clear that hydrogen imports will be needed to satisfy between 50% and 70% of demand by 2030: "A domestic supply that fully covers demand does not make economic sense or serve the transformation processes resulting from the energy transition as a whole."[185] To support ramping up hydrogen imports, Germany launched the H2Global auction program to create long-term contracts for imports at a reasonable price on the supply side, with over $1.3 billion approved to cover the cost premium of electrolytic hydrogen and reimburse sellers for delivery costs.[186] On the demand side, contracts will be short-term so expected clean hydrogen cost reduction better translates into what offtakers pay. Grants from the government will cover the difference between supply prices (production and transport) and demand prices, in an arrangement akin to contracts for differences.[187,188] To develop hydrogen clusters, the government also awarded 30 municipalities and regions funding in 2021.[189]

- **France's** national hydrogen strategy was published in September 2020 and aims to establish two giga-factories of electrolyzers to decarbonize mobility and industry. France targets 700,000 tons of low-carbon or renewable hydrogen per annum by 2030 and sets an electrolyzer capacity target of 6.5 GW by 2030 as well as a price target at $1.6/kg H_2.[190] The country pushed for hydrogen produced from nuclear to count as renewable hydrogen to help it achieve the EU's legally binding decarbonization targets and access financing from places such as the European Bank. It faced backlash from other EU countries like Germany and Spain. Ultimately, the EU established nuclear as low-carbon—neither a renewable nor a fossil fuel—which is considered a compromise and allows France to use nuclear (with low enough emissions) to help it reach its targets.[191,192]

- **The Netherlands** also published its national strategy in 2020 and laid out priorities for scaling the clean hydrogen industry, including producing hydrogen from offshore wind. This strategy accompanies the National Climate Agreement (2019) to install 3 GW to 4 GW of electrolysis capacity by 2030. Both the French and Dutch strategies highlight the importance of using hydrogen for the heavy transport sector and industry.[193]
- **Spain** and **Portugal** are focused on the production of renewable-based hydrogen, as the only EU member states that do not have technology-neutral hydrogen strategies.[194] Spain has already met its 2030 target of at least 4 GW of installed electrolyzer capacity and is now focused on mobilizing over $18 billion toward R&D and deployment of green hydrogen production projects. Because of strong investments and resources, in the first quarter of 2022, Spain accounted for 20% of the green hydrogen projects worldwide, and it already has 15.5 GW of green hydrogen capacity.[195] Portugal's national strategy, EN-H2, targets renewable hydrogen to cover 1.5% to 2% of the country's energy demand by 2030 and indicates that 2 GW to 2.5 GW of electrolysis capacity will need to be deployed. Portugal has signaled a strong interest in renewables, and in 2020 the two remaining privately operated coal plants within the country closed.[196] The large utility formerly operating one of these plants is forming a hydrogen R&D center and hub in its place to invest in a just transition.[197]

Untapped Growth Potential: Hydrogen offers strategic importance to the EU, boosting energy security and supporting carbon neutrality ambitions.[198] By 2030, Europe expects to be consuming around 20 Mt of clean hydrogen per year, 50% from domestic production and 50% from imports.[199] Long term, Europe sees hydrogen growing to around 14% of the region's total energy mix by midcentury, up from less than 2% today.[200] While there are differences at national levels, the EU's policies and plans focus heavily on green hydrogen, especially for use in heavy industries. The region's many layers of policy support for clean hydrogen are driving increasing investor interest; Europe is now home to the most planned clean hydrogen projects, even as other countries, like China, are seeing faster commercial scaling.[201]

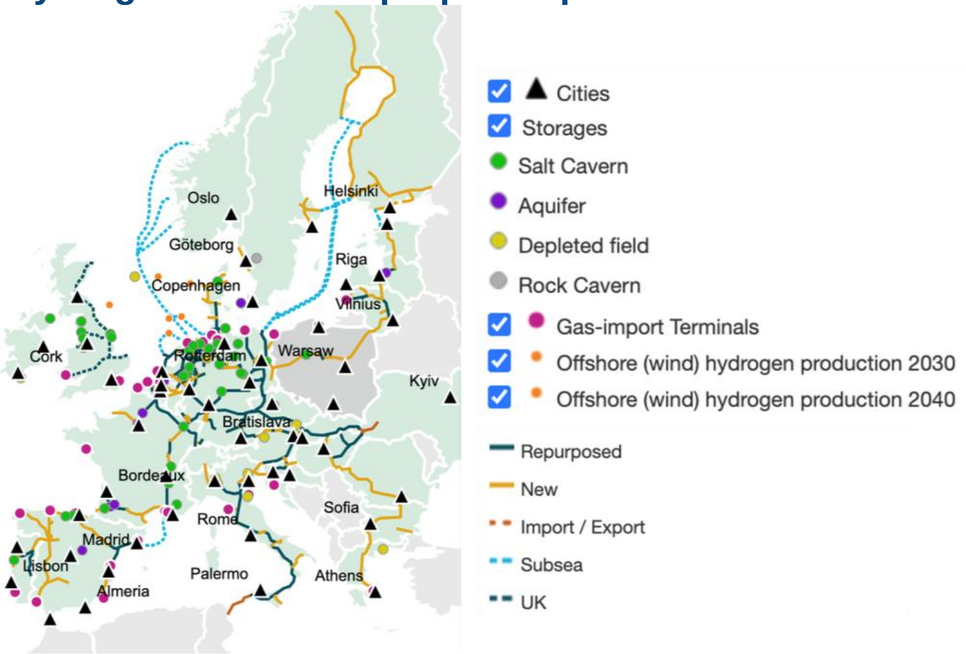
Europe's focus on green hydrogen increases the need for a low-carbon electric grid. For example, producing 10 Mt of green hydrogen would consume roughly 14% of the EU's total electricity in 2030.[202] The REPowerEU action plan projects the use of 2.3 Mt of green hydrogen in refining by 2030, decreasing gas demand of European refineries and lowering Russian gas imports by 7%.[203]

Ports with industrial clusters are emerging as important hydrogen hubs, and by 2050, 42% of total hydrogen demand in the EU could be within ports.[204] The European Union has 24 ammonia terminals and 17 methanol terminals, and several import terminals are testing the viability of different hydrogen carrier methods, including liquefied hydrogen and dedicated expanded ammonia terminals. Some terminals are expected to be operational by 2025.[205] Large companies, including Shell and Engie, are establishing the feasibility of transporting liquefied hydrogen from Sines, Portugal, to Rotterdam, Netherlands.[206] Over time, the Carbon Adjustment Border Mechanism will incentivize countries exporting to the EU to reduce the carbon intensity of hydrogen production.[207]

The European Hydrogen Backbone (EHB) is an initiative led by 32 energy and infrastructure companies to construct a dedicated network of hydrogen pipelines connecting supply and demand centers with integrated storage infrastructure (Figure 19).[208] A central component of this plan is to create hydrogen supply corridors in the North Sea and the Mediterranean, as well as in the Central European Hydrogen Corridor.

The Central corridor envisions connecting Ukraine's hydrogen supplies to demand centers in Germany. This plan, however, is dependent on geopolitical factors and may not be realized.[209, 210] Ultimately, the success of the project will depend on factors including a stable regulatory environment with strong coordination among EU countries.[211] The EHB is initially envisioned to be a 17,000-mile pipeline network connecting hubs and ports with supply, and by 2040 there could be 33,000 miles with about 60% repurposed natural gas pipelines.[212] The European Union has almost 125,000 miles of fossil fuel-based pipelines that it is considering for hydrogen use.[213]

Figure 19.
European Hydrogen Backbone proposed plan for 2030



By 2040, the European Hydrogen Backbone project will be a network connecting supply (including from outside of the EU) and demand centers (like cities) with integrated transportation and storage. This initiative will construct new pipelines and repurpose existing gas infrastructure. By 2040, the network will be further developed, particularly in areas like the North Sea. Source: See first figure mention in text for sources.

Europe has established itself as a leader in RD&D and is the global leader in hydrogen patents, holding 28% of the world's total from 2011 to 2020. Patents are attractive to startup investors, as more than 80% of late-stage investment in hydrogen startups over the past decade was directed to companies that had filed a patent application.[m,214] Hydrogen is being used in novel contexts. For example, the TULIPS project has over $27 million in funding from the European Green Deal and brings together private companies, research institutes, airports, and airlines to demonstrate hydrogen use to increase airport operations sustainability, including in ground transportation, for sustainable aviation fuels, and integrated into neighboring hotels.[215,216]

Within the transport sector, H2Accelerate is an initiative launched in 2020 by industry players, including energy and transport companies such as Shell and Volvo, that aims to

[m] Includes the U.K.

accelerate the use of hydrogen for heavy-duty trucking.[217] More than 80% of projects for hydrogen-derived fuels are in Europe. For example, TakeOff is an EU-funded project looking to lower the cost of renewable hydrogen-based sustainable aviation fuel.

These projects are partly being driven by legislation; for example, in July 2022, the REFuelEU Aviation proposal stated intentions to increase the minimum share of synthetic fuels, which may include hydrogen, from 0.04% up to 50% by 2050.[218]

The northwestern region of Europe has a high demand for hydrogen and resources to support low-carbon hydrogen including ports, industrial hubs, advanced natural gas infrastructure, offshore hydrogen storage sites (depleted oil and gas fields and salt caverns), renewable resources including offshore wind, hydropower resources in Norway, and nuclear projects within France, as well as ambitious decarbonization plans.[n] Within the EU, 82% of salt cavern storage, 88% of FCEVs, 82% of water electrolysis capacity, and nearly all CCUS projects are located in the northwestern region. The offshore wind industry will be particularly important for renewable energy generation. In 2018, the North Sea accounted for 18 GW (out of 23 GW globally) of installed capacity of offshore wind. To accommodate the rapid increase in intermittent renewable energy generation, new technologies and investments were made in the power grid to balance supply and demand, showcasing the region's extensive capabilities to support a low-carbon hydrogen economy.[219]

The high demand for hydrogen in the area surrounding the North Sea is largely driven by a strong industrial presence. For example, the Antwerp-Rotterdam-Rhine-Ruhr-Area industrial cluster, which spans the Netherlands, Belgium, and Germany, hosts 40% of global petrochemical production. This cluster is well suited to support the development of hydrogen hubs given that it has integrated pipeline infrastructure and that ports like Rotterdam and Hamburg are global trading hubs.[220]

Countries within this region are focusing on RD&D for ways to use hydrogen in hard-to-decarbonize sectors. For example, the Netherlands is looking at building up an offshore

[n] Considered to be Belgium, Denmark, France, Germany, the Netherlands, Norway, and the U.K.

electricity-hydrogen hub and equipping coastal plants with offshore CCS to use offshore pipeline infrastructure and empty gas fields. Major companies, including Engie and Gasunie, have announced large hydrogen projects within the transport sector in the Netherlands, and many entities have announced intentions to build 100 MW-capacity hydrogen projects near industrial clusters in the Netherlands.[221]

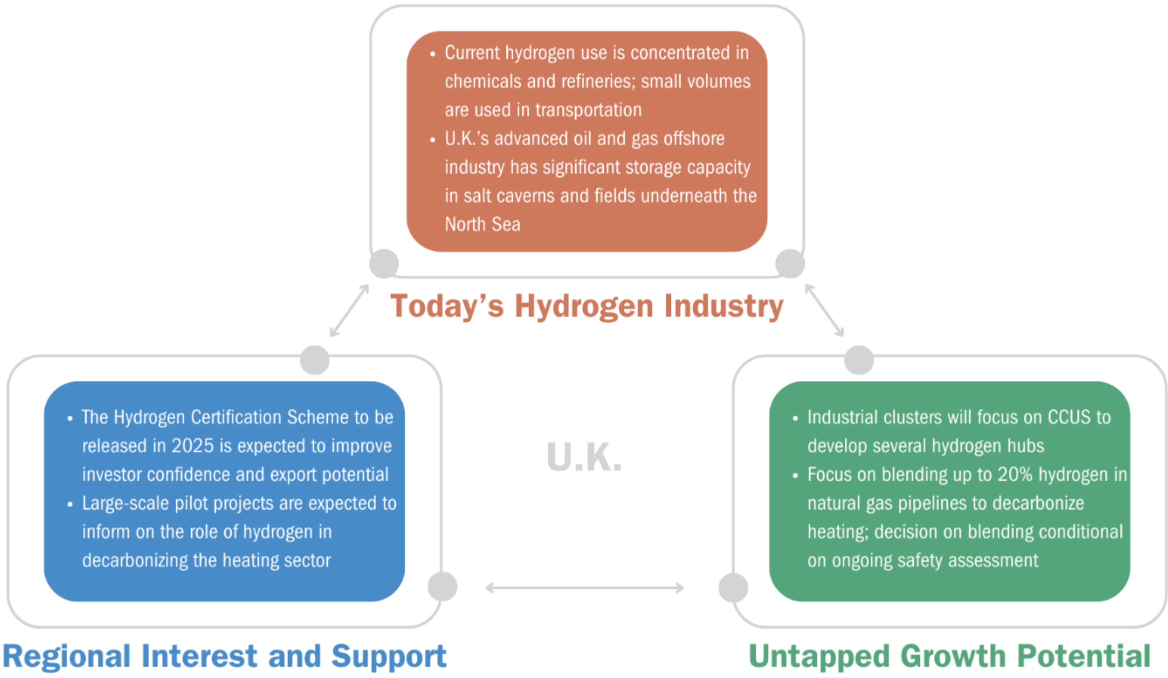
The strong industrial sector is a major factor in accelerating the market rollout of hydrogen and pushing countries like Germany to be global pioneers in hydrogen technology.[222] There are intentions to use hydrogen to decarbonize other major emitters besides heavy industry, such as mobility and the commercial heat market, and using hydrogen in buses and fleets could contribute to 10% of demand within the region by 2030. Many governments have committed to converting public transport fleets to hydrogen, which could spur uptake in public transit buses and trains. Germany has established itself as a leader in RD&D, and Europe's largest PEM electrolyzer plant is being built there.[223] Although it's working on scaling supply, Germany will rely heavily on imports to match demand, with Spain expected to become a major supplier for the country.[224]

United Kingdom

Summary: The United Kingdom remains a key player in Europe's economy and ambitions to be a leader in clean hydrogen. The U.K. sees clean hydrogen as crucial to decarbonization and for boosting energy security. The government supports both blue and green hydrogen pathways, targeting 10 GW of electrolysis capacity by 2030. The U.K. is proposing relatively modest requirements for life cycle carbon intensity of at least 2.4 kg CO_2e/kg H_2,[225] and its recently announced "certification scheme" will help verify the carbon intensity of low-carbon hydrogen.[226] The U.K. plans to leverage its current industrial base to foster development of clean hydrogen (Figure 20). Heating decarbonization is a focus, which is being supported by large-scale pilot projects to test the suitability of clean hydrogen in this application. The government is currently assessing the safety of blending up to 20% hydrogen in natural gas pipelines.

Figure 20.

U.K. Hydrogen Market Evaluation Framework summary



Today's Hydrogen Industry: Most hydrogen produced and used in the U.K. today is emissions-intensive, coming from fossil fuels with no carbon capture; only a small fraction can be called low-carbon.[227] The U.K. has used hydrogen as "town gas" for home heating and street lighting since the mid-18th century. In 2020, the U.K. produced 0.5 Mt/yr of hydrogen, mostly from natural gas reforming.[228] Chemicals and refining dominate its hydrogen industry (contributing to 90% of demand), with most production and use occurring on the same site, often integrated into a single industrial facility.[229, 230] Hydrogen is also used as a fuel, in far smaller volumes, across the United Kingdom. Hydrogen cars, trucks, buses, and marine vessels are already operating and supported by a network of refueling stations, with plans for hydrogen trains and aircraft underway.[231,232] The U.K. has around 25 miles of hydrogen pipelines.[233]

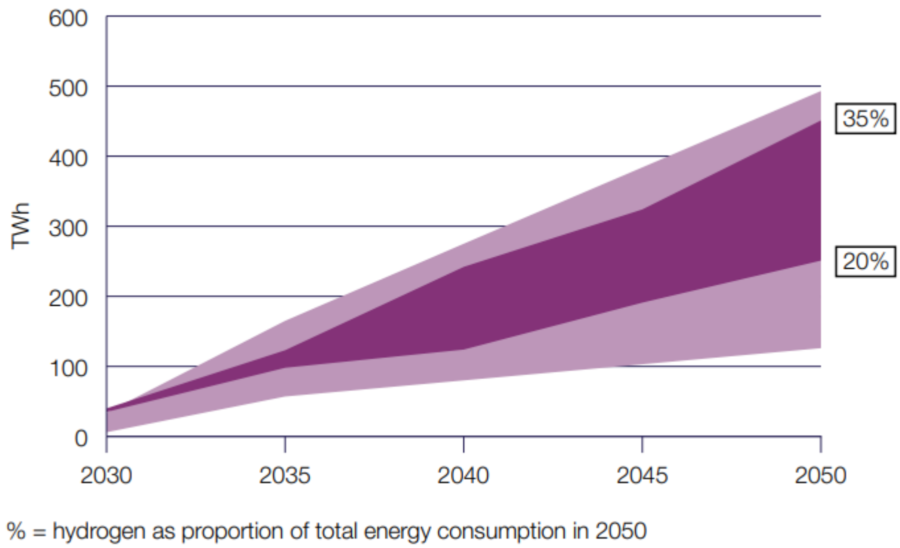
There are active clean hydrogen projects in the U.K. and emerging activities across the supply chain. Scotland, for example, is producing clean hydrogen from excess renewable resources, using it for on-road fueling, heating, and ferries. British companies, including ITM

Power and Johnson Matthey, are producing clean hydrogen-enabling technologies.[234,235] Meanwhile, the U.K.'s oil and gas industry, particularly its offshore expertise, may be crucial to scaling the country's clean hydrogen industry. Distrust of industry and public institutions is a barrier to social acceptance of hydrogen within the U.K.[236] Historically, industrial sites have generated heavy pollution that has harmed nearby communities, who are often the most impoverished groups.[237]

Regional Interest and Support: The U.K. government set legally binding targets to achieve 78% GHG emissions by 2035 and net zero by 2050, which will help drive the low-carbon hydrogen industry. [o,238,239,240] "The Ten Point Plan for a Green Industrial Revolution" (November 2020) is the U.K.'s approach to support green jobs and accelerate its path to net zero. The U.K. also released a hydrogen strategy in August 2021 to drive progress in the next decade and position hydrogen to help meet its Sixth Carbon Budget and net-zero commitments (Figure 21).[241] The strategy promotes all current and future hydrogen production to be low carbon and plans to use both CCUS-enabled (blue) and electrolytic (green) hydrogen to achieve its decarbonization goals.[242]

Figure 21.

Hydrogen demand and share of final energy consumption in 2050



[o] The Paris Agreement target of reducing GHG emissions to at least 68% below 1990 levels by 2030 is not legally binding. However, the 2035 emissions reduction target builds on the 2030 target.

To meet its net-zero commitments, the U.K. may need to scale up hydrogen adoption between 250 terawatt hours (TWh) and 460 TWh (8 Mt to 14 Mt) by 2050, equivalent to 20% to 35% of the U.K. total energy consumption. Source: See first figure mention in text for sources.

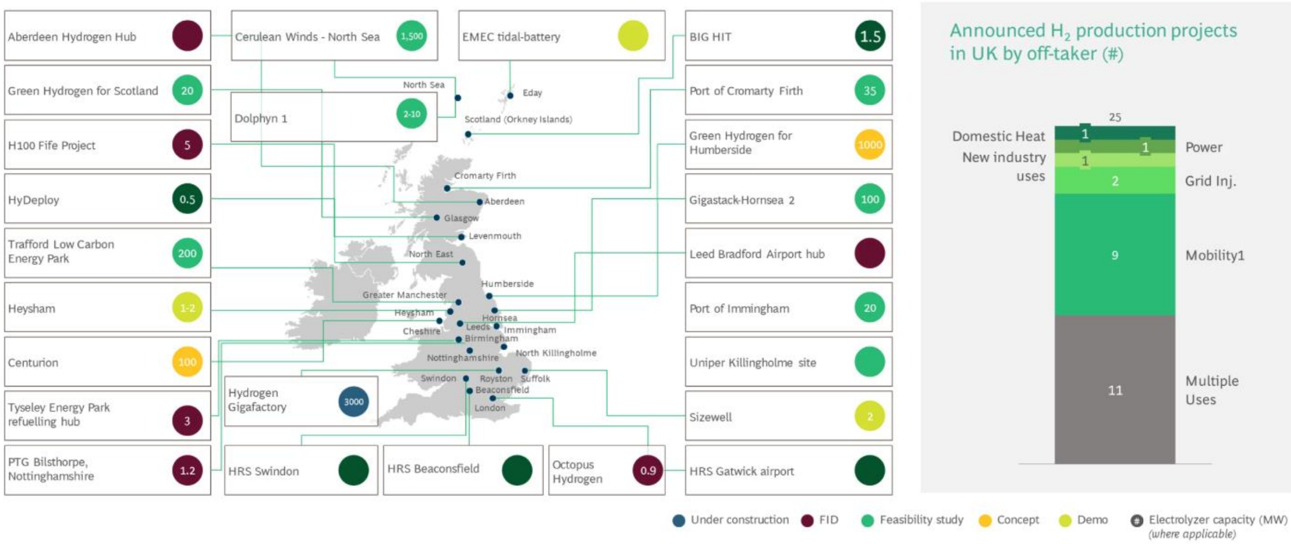
The U.K. is seeking to scale both its green and blue hydrogen capabilities, focusing on industrial regions and two primary clusters—the East Coast Cluster and Hynet—to develop hydrogen hubs in a sequencing project that will ultimately support four hubs. These projects connect participants and stakeholders across the value chain to focus on interconnectivity and heating decarbonization. They use storage underneath the North Sea. However, achieving large-scale decarbonization of sectors like heating with hydrogen will require an expansion of storage capabilities, particularly to enable CCUS.[243]

Low-carbon hydrogen is currently defined as at or below 2.4 kg CO_2e/kg H_2.[244,245] The U.K. government is working to provide regulatory certainty through visibility, and following the release of its Low Carbon Standard, it is developing a "low carbon hydrogen certification scheme" that is set to be released in 2025 and designed to improve investor confidence and export potential. In the plan, the blue hydrogen carbon capture rate must be 95% by 2030 and over 99% well before 2050.[246] Additionally, all hydrogen produced from biomass resources must meet the soil carbon, land, and forest criteria to minimize GHG emissions and biodiversity implications.[247]

In the *British Energy Security Strategy*, the government targets 10 GW of low-carbon hydrogen production capacity by 2030 with at least half produced from electrolysis. There are more than 25 major ongoing clean hydrogen projects in the U.K. (Figure 22).[248,249,250] Some regions have their own strategies; for example, the *H21 North of England* examines how to better engage the market to scale the hydrogen economy, particularly focusing on policies and frameworks to spur heat decarbonization.[251]

Figure 22.

Select U.K. clean hydrogen projects in development



Note: FID (Final investment decision)
Source: IEA (2021), Hydrogen Projects Database. All rights reserved.; Web press; BCG analysis

There are over 25 projects under development in the U.K. that focus mostly on mobility or multiple end-use applications (such as grid injection, refining, and synthetic fuels). Source: See first figure mention in text for sources.

The *Hydrogen Sector Development Action Plan*, published in 2022, focuses on opportunities to scale the hydrogen industry by improving the investment environment, building out supply chains, supporting jobs and skills, and trading in international markets for exports.[252] The government published supporting materials for each of these focus areas. The *U.K. Hydrogen Net Zero Investment Roadmap* was published in April 2023 and highlights why the U.K. is a strong investment market. It also lists barriers to further investments and spells out investment needs over time. With the road map, the government is working to catalyze further private investments by making the case for strategic opportunities within the industry and utilizing public investment tools including grants (such as the Net-Zero Hydrogen Fund and the CCUS Infrastructure Fund) to de-risk projects.[253] Additionally, the UK Infrastructure Bank has roughly $28 billion of private financial capacity to support sectors including hydrogen.[254]

The U.K. released the Net Zero Hydrogen Fund in April 2022 to provide capital grants to support deployment of hydrogen production projects. The Hydrogen Production Business Model will provide revenue support in a contracts-for-difference-style scheme to bridge the operating cost gap between clean hydrogen and existing high-carbon fuels. With capital and operating cost support, both programs are expected to contribute to about 250 MW of new production capacity.[255] In addition, the Carbon Capture and Storage Infrastructure Fund provides support for CCUS projects, and the government announced two CCUS-enabled hubs that will receive funding as part of the CCUS Cluster Sequencing Process.[256,257]

To support supply chain development, the U.K. government commissioned research into hydrogen transportation, storage, and distribution, and the manufacturing of fuel cells.[258] Additionally, in 2025, the government is planning to release business models for hydrogen transport and storage infrastructure, which will help support supply chain development.[259] The North Sea Transition Deal commits the oil and gas industry to investing $17 billion to $20 billion by 2030 in new energy technologies, reflecting the government's focus on transitioning the current workforce and infrastructure.

Untapped Growth Potential: The U.K. hosts the world's largest offshore wind industry (18% of its primary energy supply), significant geological CO_2 storage, and an advanced oil and gas industry with expertise and infrastructure, all of which are assets in the formation of a low-carbon hydrogen industry.[260] The U.K. is promoting both green hydrogen and blue hydrogen, and the U.K. Department for Energy Security and Net Zero highlighted that cost would be the major determinant to assess green versus blue hydrogen.[261] The government projects that the production of green hydrogen will be less expensive than CCUS-enabled low-carbon hydrogen by 2025, but until then, blue hydrogen is expected to be cheaper. In a study of cost drivers for hydrogen produced from offshore wind, distance to shore and the storage period were most important.[262]

Although electrolyzer manufacturing is identified as a strength in the U.K. supply chain, reducing its cost will be crucial to driving down the total cost of green hydrogen.[263] To support this effort, many universities, including Oxford and Cambridge, are researching PEM electrolyzers. While there currently are no regions in the U.K. that are considered water stressed, some areas, particularly in the southeast, are projected to become severely water stressed by 2030, largely because of climate change, high demand, and aging infrastructure.[264]

The U.K. government intends to promote hydrogen usage in four primary end-use sectors—heavy industry, power, heat in buildings, and transportation—and is providing significant RD&D support for these.[265] The government has invested large sums of money into RD&D for low-carbon hydrogen projects. Between 2004 and 2021, the government put $440 million into CCUS RD&D, and it has identified hydrogen as one of 10 priority areas for the $1.3 billion Net Zero Innovation Portfolio.[266] The $305 million Net Zero Hydrogen Fund provides further support for projects through electrolytic hydrogen allocation rounds, which are auctions where renewable energy companies compete for a contract.

The government is supporting two large-scale pilot projects to inform decision-making on the role of hydrogen in decarbonizing the heating sector: The Neighborhood Trial and the Village Trial (planned for 2024 and 2025, respectively) will use hydrogen for 100% of heating needs.[267,268] To examine strategies for the fuel cell industry, the Tees Valley Hydrogen Hub competition focuses on scaling the fuel cell vehicle industry and building hydrogen refueling stations to test hydrogen usage in different transportation methods.

As in Germany, industry is a crucial part of the U.K.'s economy and is responsible for around 16% of its emissions. There are several industrial clusters of various sizes, locations, and emissions levels across the U.K.[269] For example, the East Coast Cluster, where a CCUS-enabled hydrogen cluster is being developed, is responsible for 50% of the nation's GHG emissions. To support hydrogen for transportation, the U.K. has granted awards to Airbus to research hydrogen aircraft and sustainable aviation fuels.[270]

Decarbonizing domestic and industrial heating with hydrogen is also attracting interest given that 85% of buildings are connected to natural gas infrastructure and that hydrogen's storage abilities can address seasonal variation in heating demand without significant energy waste.[271] Further, over 80% of the U.K. population uses natural gas for heating and cooking.[272] Social acceptance of hydrogen for this novel usage will depend on many factors including cost, reliability, and safety. A study found that consumers were concerned about energy poverty in residential heating applications of hydrogen.[273] A feasibility study conducted in 2016 by gas industry leaders found that Leeds, the large city it examined, is technically and economically suitable for converting U.K.'s gas distribution networks from natural gas to 100% hydrogen with minimal cost or disruption to consumers.[274]

The U.K. is focusing on blending up to 20% hydrogen in natural gas pipelines to use its advanced pipeline infrastructure. The government's final decision will be made following the completion of industry demonstration trials to assess the safety of hydrogen blending into the Great Britain gas distribution network.[275] Conditional on the safety assessment, the government has decided to support a free-market approach to blend hydrogen into the natural gas network, injecting hydrogen into the network on a "first come, first served" basis, mimicking the existing connections to the gas networks. [276,277] Energy company National Grid also is studying the feasibility of building a U.K. "hydrogen backbone" by 2030 with support from the Net Zero Hydrogen Fund. National Grid envisions a 1,243-mile hydrogen pipeline network (69% repurposed natural gas pipelines) connecting major supply and demand centers and integrated into the European Hydrogen Backbone.[278] The U.K. is looking to hydrogen export markets mostly within the European Union, as the EU-UK Trade and Cooperation Agreement allows for zero tariff trade.[279]

Community interest groups have emerged within the U.K. so local communities/consumers and private developers can share ownership of renewable energy projects. The Shared Ownership Policy (2014) supports and encourages these ownership models, which help local communities share in the benefits of renewable energy projects.[280] Transitioning heavy-polluting and hard-to-decarbonize areas to low-carbon production pathways with hydrogen has the potential to address environmental justice concerns that disadvantaged communities are often located in industrial areas and that housing developments are located near or on degraded land.[281]

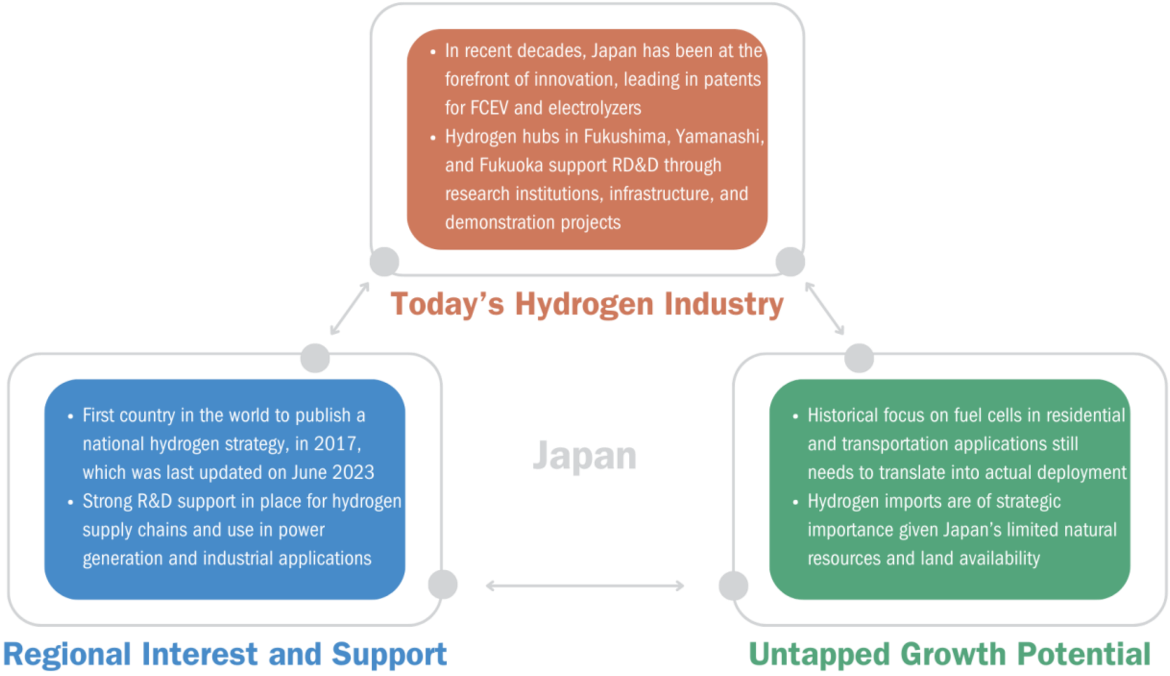
The U.K. has a skilled workforce and advanced infrastructure to build the hydrogen economy, and the government is investing in these areas to make a smooth transition to a low-carbon hydrogen economy. For example, the $70 million Industrial Fuel Switching competition is fueling innovation and growth by incentivizing the development of the low-carbon fuels industry.[282] The U.K.'s workforce is well positioned for this transition as the engineering sector alone employs 5.6 million people.[283] The Department for Education is investing $4.9 billion by 2025 to support workers, and the government has several supporting policies. The Local Skills Improvement Plan will help transition workers, and a Lifetime Skills Guarantee further supports the workforce in transition to a low-carbon economy. The North Sea Transition Deal specifically focuses on transitioning oil and gas workers, and Free Courses for Jobs and the Green Jobs Delivery Group further help workers gain the skills and qualifications necessary to be a part of the industry.[284] The U.K. is a leader in technological innovation as one of the top 10 countries for hydrogen technology patents. More than 200 U.S. companies are working on hydrogen and fuel cell technological development.[285]

Japan

Summary: Japan is a highly industrialized country dependent on energy imports due to a lack of domestic resources. In 2017, Japan was the first country to release a national hydrogen strategy, and it continues its leadership by promoting the development of its domestic hydrogen industry and international supply chains. Japan sees hydrogen as a crucial decarbonization and energy (and economic) security pathway. Historically, Japan's focus was on using hydrogen in fuel cells for residential and transportation applications. In recent years, there has been a new emphasis on using hydrogen for industrial decarbonization. Japan continues to develop international cooperation with regional partners, such as Australia and the United Arab Emirates, to build the shipping capabilities to connect to these locations with low-cost supply. Japan continues to be one of the largest government investors in hydrogen R&D programs.[286]

Figure 23.

Japan Hydrogen Market Evaluation Framework summary



Today's Hydrogen Industry: Japan produced roughly 2 Mt of hydrogen in 2020. About 50% of that production came from fossil gas reforming; 45% as a byproduct from steel, steam cracking, and the chlor-alkali process; and 5% from coal.[287] Ninety percent of hydrogen demand in 2020 was for oil refining.[288,289]

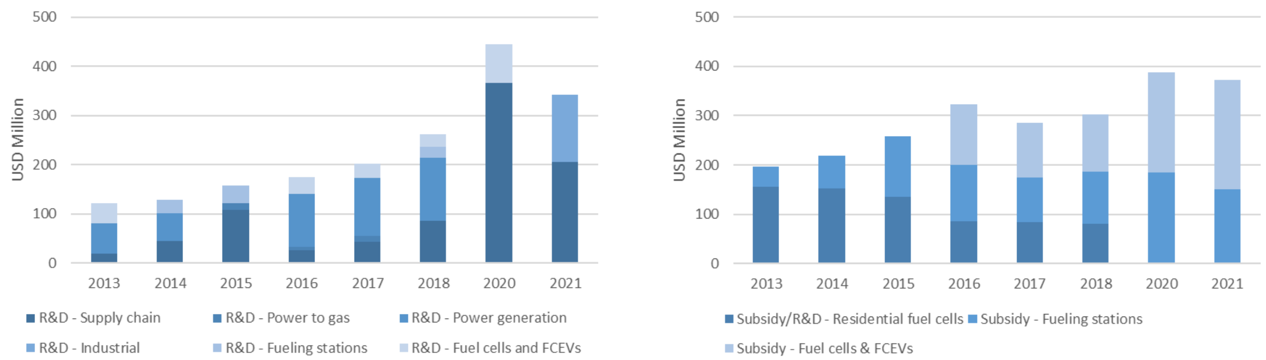
Japan imports more than 95% of the energy and chemical resources it consumes. The total primary energy supply is dominated by oil (38%), coal (27%), and natural gas (23%). Together, natural gas and coal account for over two-thirds of power generation, and hydrogen imports have been fossil fuel-based and thus emissions-intensive. Japan has worked on developing an international hydrogen supply chain to repurpose existing fossil fuel assets to support hydrogen imports.[290,291] Japan does not have any hydrogen pipelines today, although it has 13 ammonia and two methanol terminals.[292]

Japan is one of the world's largest investors in clean hydrogen technology R&D. It has developed strong technological capabilities in fuel cells and electrolyzer technologies.

Government spending during Japan's 2020 fiscal year (April 2020 to March 2021) included $247 million for clean energy vehicles (including, but not limited to, hydrogen and fuel cells), $40 million for residential fuel cells and fuel cell innovation, $52.5 million for innovative fuel cell R&D, $120 million for FCEV refueling stations, $30 million for hydrogen supply infrastructure R&D, and $141 million for the development of hydrogen supply chains to support imports.[293] As seen in Figure 24, government spending on hydrogen is split between building the R&D pipeline and subsidizing commercial projects.[294] A major focus has been on supply chain development and power generation, although there has been a recent increase in spending on industrial applications for hydrogen.[295]

Figure 24.

Breakdown of government spending on hydrogen R&D and subsidies (years 2013-2021, excluding 2019)

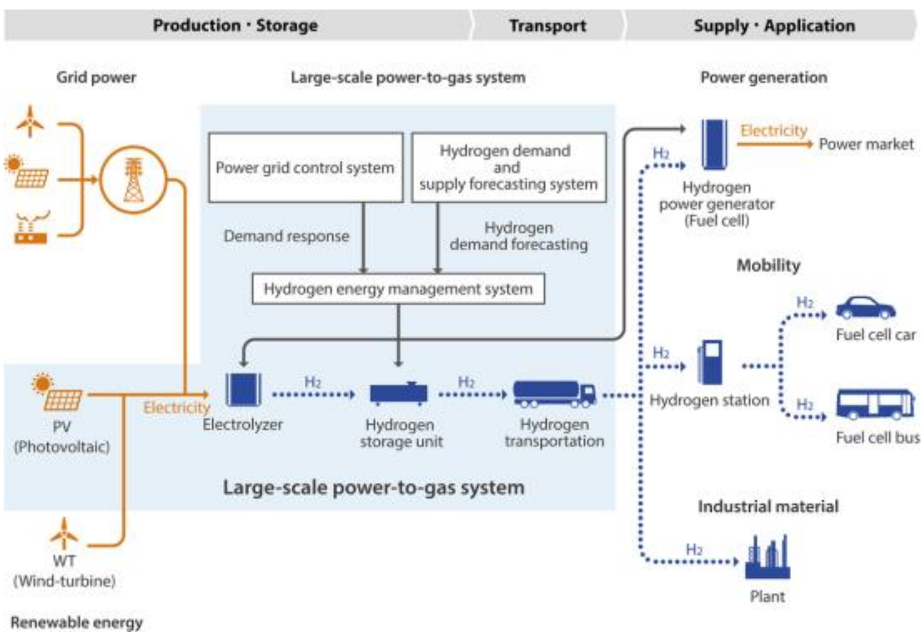


The government has historically prioritized R&D spending for supply chains and power generation, although in 2021 R&D for hydrogen use in industry increased. Subsidies target cost reduction for hydrogen applications in the mobility sector. Adapted from: See first figure mention in text for sources.

Japan has about a quarter of the world's light-duty hydrogen vehicles, and Toyota was the first company to build commercial FCEVs.[296,297] Japan has more than 130 hydrogen refueling stations, the world's second most behind China.[298,299] Fuel cells are also used in Japan's ENE-FARM technology, with around 430,000 fuel cell units providing heat and power to residents.[300] Production began in 2008, and the fuel cells are predicted to be installed in 10% of Japanese households by 2030.[301]

Japan also built one of the world's largest electrolysis plants (10 MW) in Fukushima, using solar power for hydrogen production (Figure 25).[302,303] However, while Europe and China have reached commercial-scale deployment of electrolyzers, one of two Japanese companies supplying electrolyzers is still in the demonstration stage. This lack of large-scale production is making Japan's electrolyzers more expensive.[304]

Figure 25.
Fukushima Hydrogen Energy Research Field project



The Fukushima Hydrogen Energy Research Field (FH2R) project is testing how to use hydrogen to power stationary fuel cell batteries to provide energy storage to the power grid in a large-scale power-to-gas system. Source: See first figure mention in text for sources.

Regional Interest and Support: By FY 2030, Japan aims to cut GHG emissions by 46% from FY 2013 levels, and it aims to achieve carbon neutrality by 2050.[305] Japan sees hydrogen as a key component for reaching net-zero targets. Japan's hydrogen strategy, revised in 2023, created targets of 12 Mt of clean hydrogen by 2040, with a carbon-intensity requirement of at least 3.4 kg CO_2e/kg H_2. The Japanese government has sought to raise public awareness of its vision for a hydrogen-based society through initiatives like a museum in Tokyo.[306]

In December 2020, Japan released its *Green Growth Strategy Through Achieving Carbon Neutrality in 2050*, which includes an action plan for hydrogen as one of 14 growth sectors. This strategy provides grant funding through the Green Innovation Fund of approximately $14 billion over 10 years (aimed to stimulate roughly $110 billion in private investments) toward achieving carbon neutrality, as well as tax incentives aimed to stimulate roughly $12 billion of private investments over 10 years.[307]

In June 2021, Japan updated the *Green Growth Strategy* to accelerate decarbonization and advance incentives for necessary technology including hydrogen. The strategy highlights the importance of making hydrogen cost-competitive with natural gas.[308,309]

Several additional energy policies provide support for low-carbon hydrogen. The 6th Strategic Energy Plan (published roughly every three years) increases the contribution of non-fossil fuel sources to the power mix from 24% in FY 2019 to 59% in FY 2030 (including 20% to 22% from nuclear), which has the potential to increase the production of low-carbon hydrogen. Additionally, the plan states hydrogen/ammonia should make up 1% of the power mix. This plan also pushes for hydrogen to be used in industry, particularly in steelmaking.[310]

The government is targeting the price of low-carbon hydrogen to be at $3/kg by 2030 and $2/kg by 2050 and hopes ultimately to make renewable-based hydrogen more competitive than hydrogen produced from fossil fuels (assuming a price charged for CO_2 emissions).[311] The Japanese Ministry of Economy, Trade and Industry has also set electrolyzer efficiency targets at 70% by 2030 (the global average is currently around 65%[312]) with the expectation that green hydrogen technologies will be profitable at this point.[313]

Several policies provide incentives to reach these ambitions. The Basic Policy for the Realization of GX (Green Transformation) includes several financial initiatives with public-private investments totaling around $1.1 trillion over the next decade for energy supply sources including hydrogen, and the revised Japan Oil, Gas, and Metals National Corporation Act increases financial assistance to hydrogen and ammonia projects.[314,315]

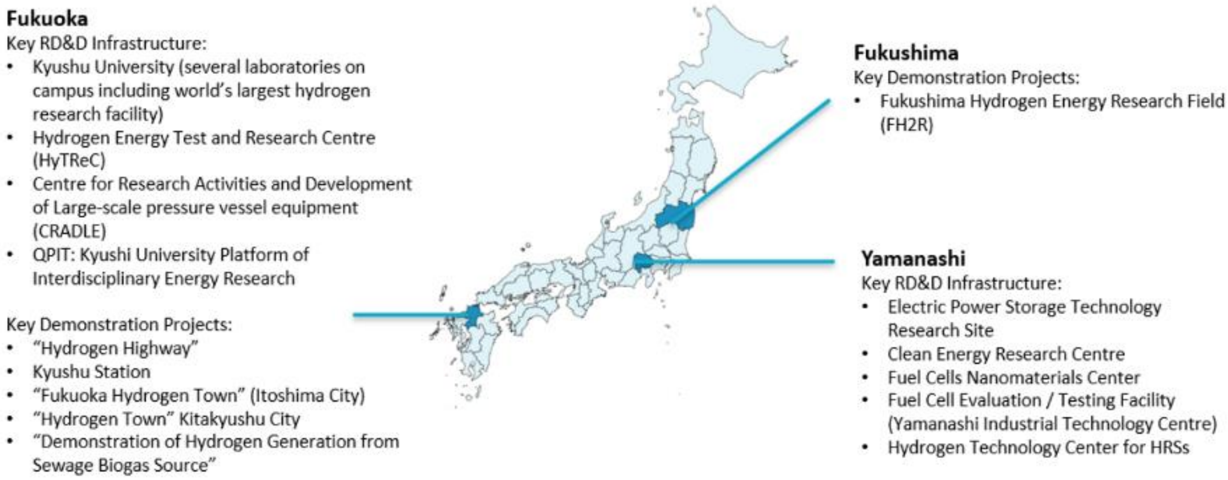
The revised Basic Hydrogen Strategy proposes that the hydrogen supply reaches 12 Mt (includes ammonia and imports) by 2040.[316] The strategy also discusses the potential use of a contracts for differences (CfD) subsidy scheme to close the price gap between green and gray hydrogen and focuses on building out a hydrogen supply chain and new infrastructure.[317,318]

Additionally, the plan implements a new safety strategy.[319] GX Economy Transition Bonds have been in high demand and, with government backing, allow investors to support the issuer's lower-carbon transition. This system has allowed airlines to sell bonds to buy fuel-efficient jets or invest in fuels including hydrogen.[320] An Emissions Trading System and carbon tax will push low-carbon hydrogen production.[321]

Fukushima, Yamanashi, and Fukuoka prefectures have emerged as large potential hydrogen hubs. Due to a high reliance on imports, hub development in port areas has been important (Figure 26).[322] These cities have brought together many stakeholders. For example, Yamanashi Prefecture is home to the University of Yamanashi's Fuel Cell Nanomaterial Research Center, demonstration projects for power-to-gas and green hydrogen production, and multiple end-use applications including factories utilizing hydrogen for industrial heating.[323,324]

Japan is working to develop additional hydrogen hubs. As part of the revised Hydrogen Strategy, Japan plans to invest in hub development in three large-scale city projects and five medium-scale hubs.[325] Private companies are participating in hub formation as well, and 11—including Mitsubishi Chemical, Toyota, and Air Liquide—established the Hydrogen Utilization Study Group in Chubu Prefecture in March 2020 to examine opportunities and challenges for developing Chubu into a hydrogen hub.[326]

Figure 26.
Japan's hydrogen hubs



Fukuoka, Fukushima, and Yamanashi have all emerged as important hydrogen hubs. These clusters support RD&D through research institutions, infrastructure, and demonstration projects. Source: See first figure mention in text for sources.

Untapped Growth Potential: Hydrogen is strategically important to Japan given its limited natural resources and land availability.[327] By 2030, Japan hopes to scale its import and domestic production of clean hydrogen. After 2030, Japan will focus on greening its supply and decarbonizing existing production through methods like CCUS.[328]

Japan also has set hydrogen consumption targets for midcentury, including 800,000 light-duty passenger FCEVs, 50% or more ammonia co-firing in power generation, and replacing traditional residential energy systems, gas stations, and conventional fossil fuel cars, buses, and forklifts with hydrogen (Table 2).[p,329,330] The government envisions ammonia imports being used for power generation where ammonia has the potential to be used directly as a fuel.[331] Co-firing hydrogen and ammonia for power generation is important for Japan's strategy so the nation can continue to use coal plants and avoid stranded asset risk. Around 2030, the country aims that hydrogen power generation will be commercially available.[332]

[p] Ammonia co-firing technology in coal-fired power.

Table 2.

Targets set forth by Japan's Basic Hydrogen Strategy (2017), the Green Growth Strategy (2021), and the revised Hydrogen Strategy (2023)

	Current	2030 Target	2040 Target	2050 Target
Hydrogen supply volume*	~2 million tons per year	3 million tons per year	12 million tons per year	20 million tons per year
Landed cost	~$10/kg (100 JPY/Nm3)	~$3/kg (30 JPY/Nm3)	-	Less than ~$2/kg (20 JPY/kg)
Stationary fuel cells	338,000 units installed (2021)	3 million ENE-FARM units	-	Complete replacement of traditional residential systems
Power generation	~$0.68/kWh (97.3 JPY/kWh) (2021)	$0.12/kWh (17 JPY/kWh)	-	~$0.083/kWh (12 JPY/Nm3)
	Co-firing technology 20% in coal plants developed	Expansion of 20% co-firing across industry		50% or more co-firing ratio in 2030s and start single-fuel firing in 2040s
Hydrogen stations	154 (2021)	~1,000	-	Replacement of gas stations
FCEVs (passenger)	4,100 (2021)	800,000	-	Replacement of conventional fossil fuel cars
FC buses	100 (2021)	1,200	-	Replacement of conventional fossil fuel buses
FC forklifts	250 (2020)	10,000	-	Replacement of conventional forklifts

*Including imports and ammonia

Data from: See first table mention in text for sources.

Japan would like to use hydrogen to decarbonize sectors such as electric power generation (fuel cell, use in power generation turbines), transportation (automobile, shipping, aircraft, railway), and industries (steelmaking, chemical, petroleum refining).[333] The government has heavily focused on uses in power generation and light-duty transportation over sectors like heavy-duty transportation and industrialization that have been instrumental in driving demand interest for hydrogen in other countries; uses in power generation and light-duty transportation are expensive compared with other technologies including electric batteries and renewable electricity generation.[334,335]

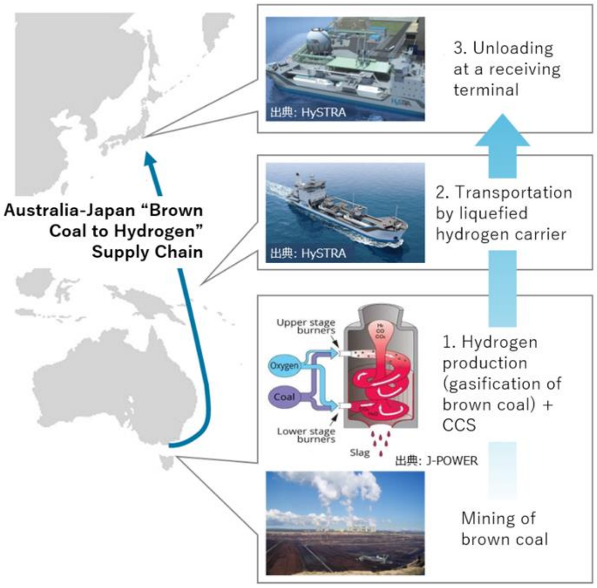
Industrialization is a vital part of Japan's economy, and hydrogen's potential to decarbonize this sector is important for the country's climate ambitions and international competitiveness.[336] However, the high cost of green hydrogen will hinder demand for use in decarbonizing high-emitting sectors such as steelmaking.[337]

Japan is a leader in fuel cell technology, especially FCEVs, and Japanese leaders are seeking to export this technology to the rest of the world.[338] Japan's FCEV deployment targets will help bolster demand and drive growth within this sector.[339] The Japanese government will strengthen international competitiveness by focusing on the fields of Japanese companies' technological expertise where growth is expected, such as hydrogen power generation turbines, commercial vehicles including fuel cell trucks, and hydrogen reduction steelmaking.[340]

Japan also has opportunities to build upon existing regional workforce strengths to accelerate the formation of its hydrogen economy. Notably, the Tokai region has vehicle manufacturing expertise where FCEVs can be built, and Minami-Kanto has a high number of workers in the fossil fuel power and petrochemical sectors whose jobs will be at risk in the energy transition.[341]

Hydrogen imports could provide low-cost and low-carbon hydrogen for Japan.[342] Japan's reliance on imported LNG has supported the development of port infrastructure, which has the potential to be repurposed for hydrogen. To support the international supply chain, the Japanese government is currently exploring all hydrogen carrier options including via liquefication, methylcyclohexane (MCH), and ammonia. With support from the Green Innovation Fund, Japan's Kawasaki Heavy Industries Ltd. built the world's first liquefied hydrogen vessel and liquefied hydrogen receiving terminal, which received a shipment from Australia in 2021 (Figure 27).[343,344] The government is targeting commercialization of liquefied hydrogen and MCH technologies by 2029 and 2030, respectively.[345]

Figure 27.
Shipment of liquefied hydrogen from Australia to Japan



Australia is expected to be a major hydrogen supplier to Japan. The first trip was successfully completed using liquefied hydrogen. The hydrogen was produced from coal in Australia. Source: See first figure mention in text for source.

Japan has taken multiple steps to secure diversified supply sources in the international market. The country received the first shipment of blue ammonia (globally) from Saudi Arabia and a shipment of natural gas-based hydrogen from Brunei with MCH as the carrier.[346] Japan plans to use large amounts of imported hydrogen for generating power, and co-firing imported ammonia in existing power plants will be helpful to reduce CO_2 emissions.[347]

The public and private sectors have been active in developing the hydrogen economy across the value chain. There has been strong collaboration, particularly through the Carbon Neutral Port Initiative and the Public-Private Fuel Ammonia Council. Stakeholders, including companies and financial institutions, have been joining forces through the creation of groups such as the Japan Hydrogen Association to improve conditions for market development.[348]

Around 2030, Japan envisions transitioning to clean hydrogen through production from domestic renewables and with the utilization of CCUS.[349] In light of the 6th Strategic Energy Plan's ambitions to increase nuclear generation, the Japanese government is supporting a demonstration project studying the feasibility and cost of producing hydrogen from nuclear reactors.[350] Japan is also a world leader in solar photovoltaic (PV) production, which could be an asset in the production of green hydrogen.[351] However, the high cost of renewables production, partly due to Japan's limited land area, makes solar PV better suited for electricity generation, as there is energy loss when converting electricity to hydrogen.[352]

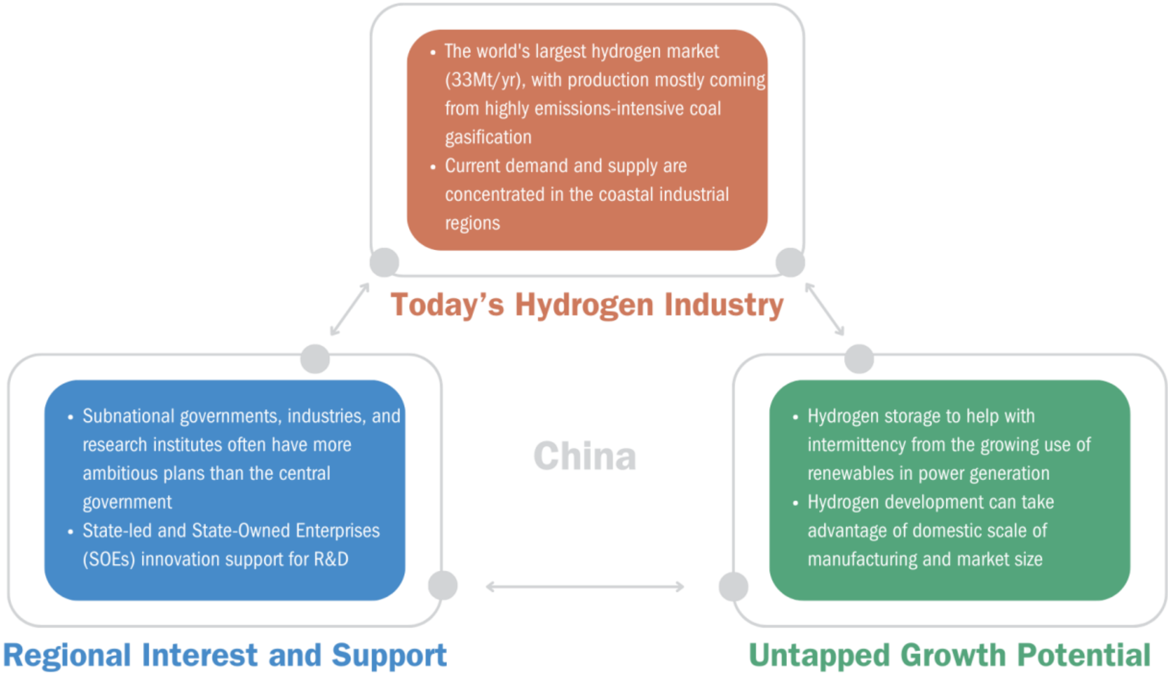
The government provides robust funding for RDD&D while keeping its technology options open.[353] The Green Innovation Fund will invest around $14 billion over 10 years. As part of this fund, roughly $2.7 billion is allocated to establishing a large-scale hydrogen supply chain and $700 million for advancing the production of renewable-based hydrogen with a focus on driving down the cost of electrolyzer production.[354,355] Additionally, the fund includes tax incentives to support the decarbonization of hydrogen production facilities and RD&D, with the aim of stimulating around $12 billion of private investment over 10 years.[356,357]

From 2011 to 2020, Japan held 24% of hydrogen patents globally—only Europe had more. Japan holds over half of the world's patents for FCEVs, which benefited from synergies with electrolyzer technology, as well as 52% of water electrolysis patents filed from 2005 to 2020.[358,359,360]

China

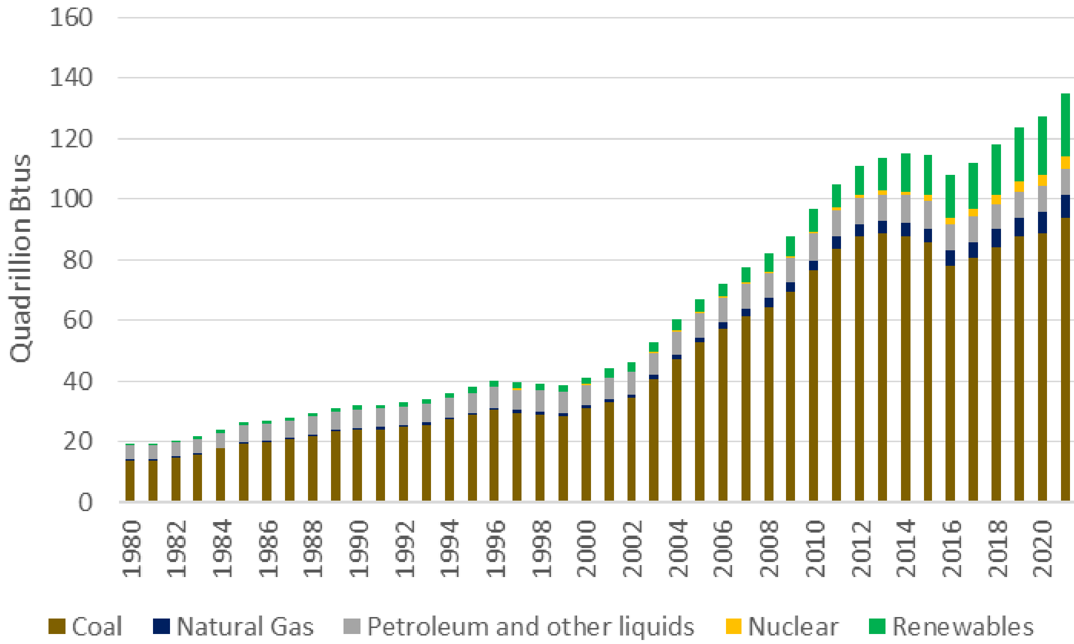
Summary: Currently the world's largest hydrogen producer and consumer, China aims to use its manufacturing expertise, market size, and government support to foster its clean hydrogen industry (Figure 28). The central and provincial governments are driving clean hydrogen development. The central government laid out medium- and long-term plans for hydrogen, targeting up to 0.2 Mt of green hydrogen production by 2025 to support 50,000 FCEVs.[361] China's interest in economywide decarbonizing and sustaining economic growth drives its interest in clean hydrogen. There is also interest in using clean hydrogen for decarbonizing industry and power generation. China's clean hydrogen targets appear relatively modest considering other national plans and the country's current position as the world's largest hydrogen market. Another major focus for the central government is expanding its hydrogen R&D support.

Figure 28.
China Hydrogen Market Evaluation Framework summary



Today's Hydrogen Industry: China is the world's largest producer and consumer of hydrogen, representing 30% of the global market, or 33 Mt/yr. China is also one of the fastest-growing hydrogen producers, with output increasing by nearly 7% per year since 2010. The growing supply is driven by the country's expanding refining sector.[362] In China, hydrogen is mostly produced from coal gasification (63%), driven by coal's role in the country's energy mix (Figure 29).[363] Coal gasification is highly emissions-intensive at an estimated 20 kg CO_2e/kg H_2,[364] roughly twice that of steam methane reforming, contributing to hydrogen production accounting for 360 Mt of CO_2 emissions in China.[365] Hydrogen is also produced in China as a byproduct of other processes (21%), through natural gas reforming (14%), and via water electrolysis (1% to 2%).[q,366] In 2021, less than 0.1% of hydrogen produced through electrolysis was powered by renewable energy sources.[367]

Figure 29.
Annual primary energy production in China



Coal is currently the main energy source in China, responsible for 70% of total energy supply. Its predominance, however, has been decreasing because of the growth of renewable energy, whose participation in China's energy matrix has increased to account for 15% of energy production. Data from: See first figure mention in text for sources.

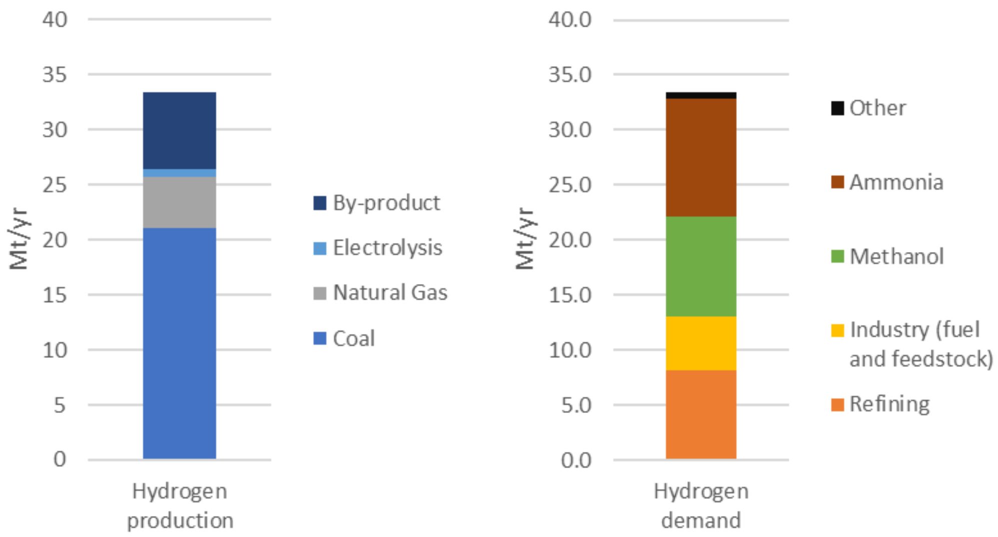
China's current demand for hydrogen is largely concentrated within the country's industrial regions. Hydrogen is used mostly as a feedstock in industrial processes, particularly for refining and ammonia and methanol production (Figure 30).[368] Less than 0.02 Mt is consumed for transportation (mostly FCEVs) and other end uses.[369] By 2021, there were 9,000 hydrogen fuel cell vehicles on the road, all of which were trucks and buses; the nation has almost 95% of the world's fuel cell buses and leads in the development of fuel cell trucks.[370,371] At the Beijing Olympics in 2022, the country presented 1,000 fuel cell buses powered by Chinese-made fuel cells.[372] China has around 200 refueling stations, the most

[q] Hydrogen is made as a byproduct of several processes in China: coal-coking in steelmaking, chlor-alkali electrolysis in chlorine and caustic soda production, dehydrogenation, cracking of light oil fractions, and catalytic naphtha reforming.

of any country, and many of them can charge buses and trucks as well as passenger vehicles.[373,374] To transport hydrogen, China mostly relies on trucks. The country's natural gas pipeline network is extensive, more than 69,000 miles,[375] but China has been falling behind other places like the United States and Europe in blending feasibility studies. Some progress has been observed lately as the country has successfully transported a 24% blend of hydrogen with natural gas through a 240-mile pipeline.[376,377]

Figure 30.

Hydrogen production and demand in China, 2020



The majority of China's hydrogen is produced from coal. Hydrogen is currently used mostly for ammonia and methanol plants as well as oil refineries, with some applications in the transportation sector. Source: See first figure mention in text for sources. Notes from source: "By-product hydrogen includes hydrogen produced from coal-coking in steelmaking; chlor-alkali electrolysis in chlorine and caustic soda production; dehydrogenation; cracking of light oil fractions; and naphtha catalytic reforming. Dedicated hydrogen production and by-product hydrogen from catalytic naphtha reforming amount to around 26 Mt."

The maximum life cycle carbon emissions for hydrogen to be considered low-carbon in China is 14.51 kg CO_2e/kg H_2, while the threshold for clean hydrogen is 4.9 kg CO_2e/kg H_2. China's standard is the first that categorizes definitions based on production methods. The threshold for low-carbon is exclusively for hydrogen produced through coal gasification. When the threshold for clean hydrogen is met, hydrogen produced through electrolysis or using biomass can also be labeled as renewable hydrogen.[378]

Regional Interest and Support: The Chinese government has designated hydrogen as a priority in its most recent Five-Year Plan, a major development as China often achieves rapid market scale, including wind and solar, through state-driven strategic policies and investment.[379] This is opening many investments in human capital and financial resources for the industry.[380] The country's Medium- and Long-Term Plan for the Development of Hydrogen Industry (2021-2035) put hydrogen development into national development policy and established that increasing renewable-based production would be important in the medium to long term.[381] Additionally, this plan targets 0.1 Mt to 0.2 Mt of hydrogen production and 50,000 FCEVs on the road by 2025.[382]

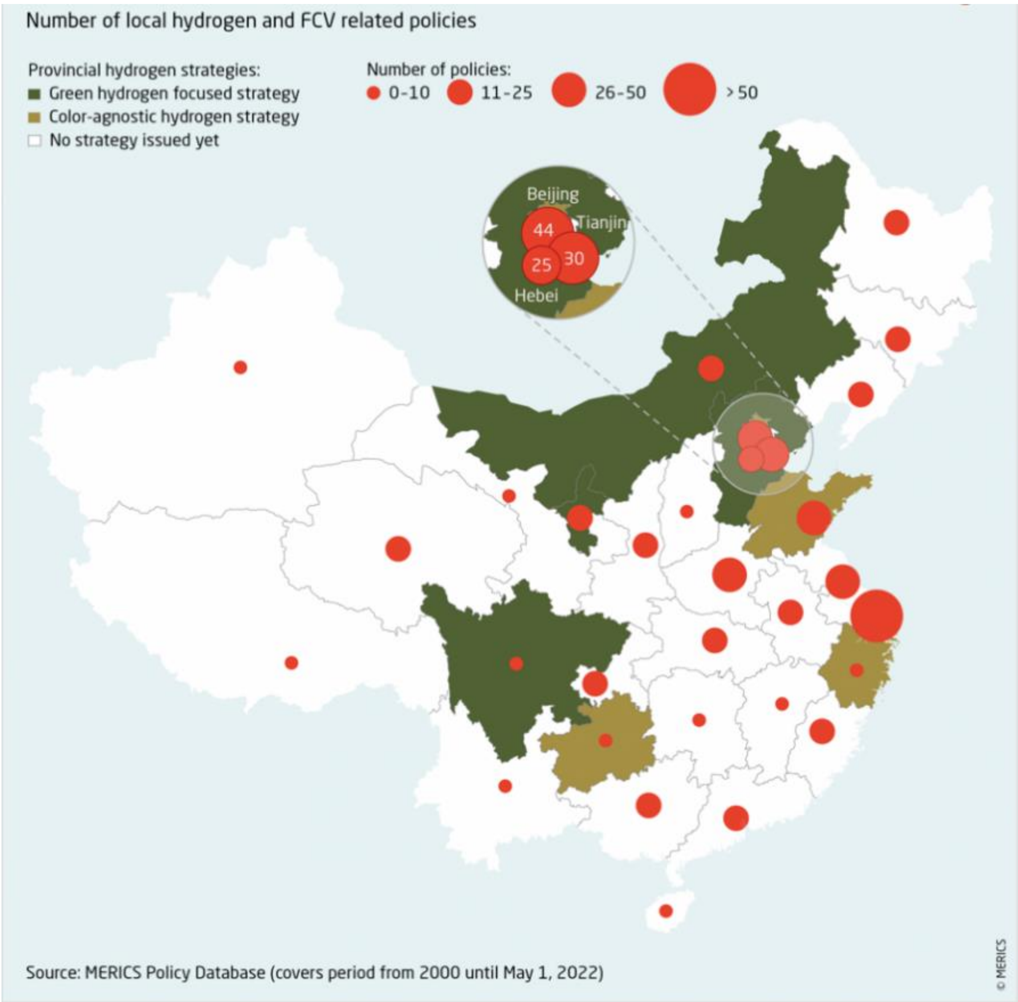
Given the vast amount of clean energy deployment that will need to occur as the world's largest GHG emitter, China's goals of reaching peak CO_2 emissions by 2030 and carbon neutrality by 2060 are creating bullish forecasts for the clean hydrogen industry.[383] Additionally, China extended its New Energy Vehicle (NEV) Tax Reduction and Exemption Policy to 2027 to accelerate the transition to NEVs, which include battery electric vehicles, fuel cell electric vehicles, and plugin hybrids.[384] The China Hydrogen Alliance—a government-supported industry group established in 2018—has been a particularly strong advocate for the hydrogen industry and started several initiatives including for the installed capacity of electrolyzers to reach 100 GW by 2030, which could produce approximately 7.7 Mt of green hydrogen per year.[385]

At least 53 large-scale hydrogen projects have been announced, around half of which are linked to transport applications.[386,387] According to one estimate, these projects represent over $180 billion of investments. Subnational governments, industries, and research institutes are leading the push for rapid market formation and often have more ambitious plans than the central government does.[388] Nearly 30 local governments included hydrogen in their 14th Five-Year Plans, 50 cities have issued their own hydrogen strategies, and nine provinces have major development plans to scale up the hydrogen industry (Figure 31).[389] These plans have allowed regions to develop hydrogen strategies based on their particular resources, capabilities, and demand.

For example, Shanghai released a medium- and long-term plan for developing its hydrogen industry (2022-2035) with a particular emphasis on the utilization of its ports and maritime applications.[390,391] Shandong Province is hoping to be a hydrogen transportation corridor by 2025.[392] Inland regions mostly incentivize green hydrogen because of their abundant supply of renewable resources, while coastal regions are more likely to favor color-agnostic policies.[393] Although there are benefits to developing hydrogen on a regional basis, better cross-regional collaboration could stimulate further industry development.[394]

Figure 31.

Number of regional and local government hydrogen policies



Provincial governments in China have released their own strategies and/or policies supporting hydrogen development. Some focus on green hydrogen uptake, while others are color agnostic. Source: See first figure mention in text for sources.

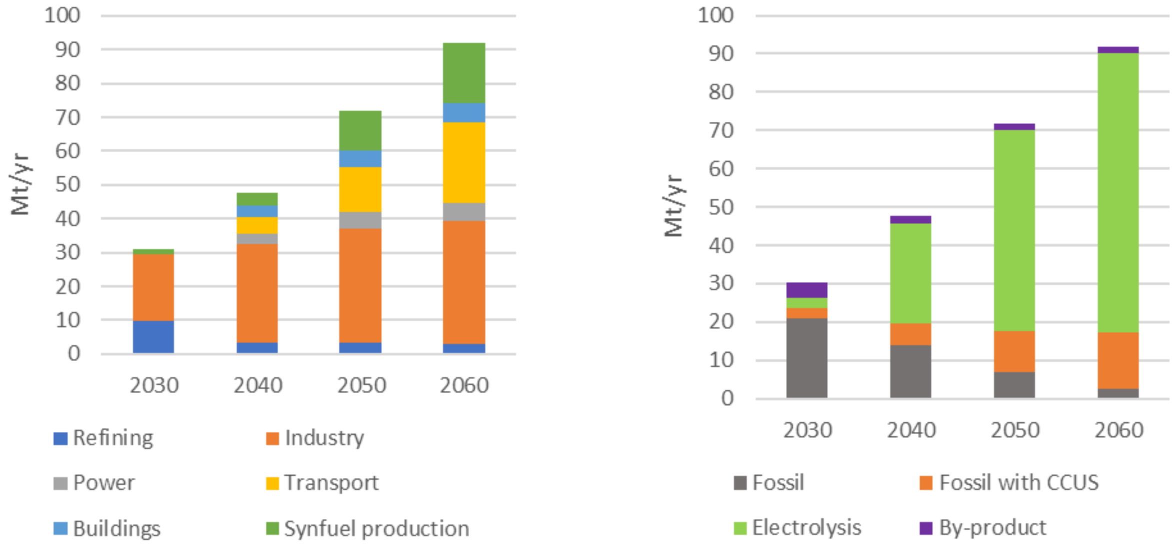
State-Owned Enterprises (SOEs) control most of the energy and heavy industry sectors and are primary drivers of new clean hydrogen investments and demonstration projects. Approximately one-third have incorporated hydrogen into future business plans.[395] Notably, one of these SOEs, Sinopec, “aims to become a new energy powerhouse that pioneers hydrogen production innovation in China, facilitating China and beyond to achieve low-carbon targets in the coming years.”[396] The government takes on many of the risks of energy projects, so companies have little incentive to engage with communities.[397] Clean hydrogen may help improve the air quality of China, which is a priority for communities and a national policy goal.[398]

The national government is funding research in public universities and research institutions, particularly through National Key R&D Programs.[399] The government is also investing in many demonstration projects. For example, the Ministry of Science and Technology is supporting Shandong (in the northeast) through the R&D program Hydrogen into Households, which will create the first provincial-scale hydrogen demonstration project focused on industrial parks, community buildings, transport and mobile energy consumption, as well as ports and highways. Investments will exceed $1.45 billion.[400]

Untapped Growth Potential: There are many reasons why China has major long-term growth potential for clean hydrogen in China. Projections see China’s clean hydrogen demand between 100 Mt and 130 Mt by midcentury (Figure 32).[401,402] The hydrogen industry could be important for China to spur technological innovation, reduce reliance on imported energy sources, and reach carbon-neutrality targets, particularly in hard-to-abate sectors. The government is primarily focused on using hydrogen for transportation (mostly for heavy-duty vehicles, rail, and aviation) and industrial applications.[403] Hydrogen’s ability to be produced from abundant domestic resources like coal, solar, and wind is essential to energy security and lowering energy costs.

Figure 32.

Outlook for hydrogen demand (left) and production (right) in China in the Announced Pledges Scenario*



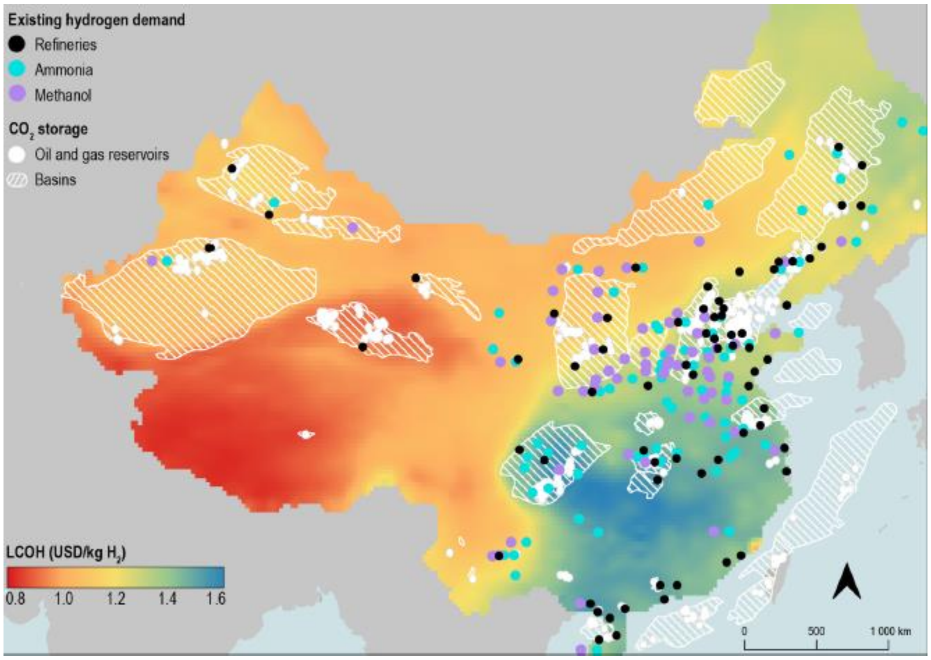
*Hydrogen demand is dominated by industrial applications, although new demand in the medium and long term is expected mostly for transport and synthetic fuel production. In the long term, renewable-based hydrogen production is expected to generate the most growth in the industry, with CCUS applications increasing and fossil fuel-based hydrogen production decreasing. *The Announced Pledges Scenario considers all fuels and technologies needed to fulfill the government's pledge of peaking CO_2 emissions before 2030 and reaching carbon neutrality by 2060. Source: See first figure mention in text for source. Notes from source: "'Industry' includes merchant and onsite use of hydrogen for heat and as a feedstock in all industry subsectors, including methanol and ammonia (for fertilizer). 'Synfuel production' includes production of ammonia as a fuel. 'Buildings' includes hydrogen for blending in the natural gas network."*

China's R&D spending on hydrogen is now larger than that of Europe and the United States combined.[404] Public sector investment in hydrogen-related R&D increased sixfold from 2018 to 2019.[405] In the first quarter of 2022, 92% of investments in the hydrogen industry went into fuel cell development, supporting expectations of high growth within this sector.[406] The majority of the approximately 120 green hydrogen demonstration projects within the country have been financed by large energy SOEs, and these enterprises have led considerable technological innovation; for example, one recently developed the largest single-cell alkaline electrolyzer.[407]

Comparing China's current hydrogen industry with some of the necessary components of a clean hydrogen industry shows strong overlap (Figure 33).[408] Many of China's heavily industrialized regions have provincial governments that support clean hydrogen R&D and also have the country's largest research institutes, workforce, and infrastructures.[409,410] China leads globally in renewable energy generation, and renewable resources—mostly wind and solar—make up 45% of the power system's capacity.[411, 412]

Figure 33.

Existing hydrogen demand, clean energy resources, and CO_2 storage potential



Existing hydrogen demand for refineries, ammonia plants, and methanol plants is located primarily in coastal regions, particularly in the northeast. There is plenty of co-location with CO_2 storage sites, which is beneficial for integrating current hydrogen production with CCUS technologies. Source: See first figure mention in text for sources.

To unlock the potential of the clean hydrogen industry, several barriers will need to be overcome. Policies incentivizing green hydrogen over other forms of hydrogen will affect the pace at which the industry grows. Reducing costs of electrolyzer technology as well as the production of renewable-based electricity is necessary for making green hydrogen cost-competitive with other forms.[413] As such, China is rapidly expanding its manufacturing of electrolyzers, accounting for one-third of global electrolyzer manufacturing capacity.[414] Water stress is also an important issue for China that could affect hydrogen production, as water is a key input for most production pathways. With only 62 miles of hydrogen pipelines, China's existing network may be insufficient for connecting expected future supply and demand.[415,416] The lack of technical and design standards for hydrogen pipelines was identified by the World Economic Forum as a barrier to infrastructure buildout.[417]

Finally, 80% of China's future hydrogen production is expected to be met with renewables and 16% from fossil fuel plants utilizing CCUS technology.[418] China has the advantage of economies of scale; the domestic scale of manufacturing and market size has often allowed for the development of relatively inexpensive clean energy technologies.[419] To decarbonize existing hydrogen production, CCUS may be important for regions with coal resources.[420] Many coal plants were constructed recently and thus represent major stranded asset risk, and in the medium term, CCUS will be the most cost-effective option for hydrogen production.[421] The country has strong potential for CCUS application given the proximity of existing demand to CO_2 storage (as seen in Figure 33 above). Almost 80% of ammonia and methanol plants as well as oil refineries are located within roughly 62.1 miles of potential CO_2 storage.[422] However, there are few projects currently utilizing CCUS within China, and the technology remains at a nascent stage.[423]

Conclusion

Regions across the world are looking to form markets for clean hydrogen to reach strategic goals, particularly in relation to decarbonization and, in many regions, enhancing energy security. However, these markets are still at a nascent stage of development, and there is currently little production or demand. The high cost of producing clean hydrogen is hindering supply and demand, so governments around the world are instituting mechanisms to scale industries, including investments in RD&D, production tax credits (Canada and the United States), cost reduction targets (Japan and the United States), and massive subsidies for innovation across the value chain. The hydrogen landscape is complex, particularly given the multitude of potential production routes and end-use applications.

The EFI Foundation's three-layered framework organizes information for stakeholders into three categories: Today's Hydrogen Industry, Regional Interest and Support, and Untapped

Growth Potential. Under each category, there are several questions regarding the factors to consider when examining a hydrogen market within a region.

As the case studies demonstrate, industry advancement and the formation of a stable investment environment rely on many factors and will vary by region. For example:

- **Supply and demand**: Variations in the abundancy of hydrogen inputs (e.g., Canada is rich in feedstocks for clean hydrogen, while Japan is focused on importing its hydrogen) shape a region's opportunities. The extent to which the government is providing supply- and demand-side support will influence regional projects.
- **Infrastructure:** Infrastructure is essential to connecting supply and demand, and plans such as the European Hydrogen Backbone will support the growth of the industry within the region. Cost reduction for hydrogen transportation and storage relies on certain factors including the ability to repurpose natural gas pipelines and build hydrogen ship carriers. The viability of CCUS-enabled hydrogen will be affected by geological formations and their storage ability.
- **Technology:** Technological innovation and scaling manufacturing of technologies like electrolyzers and fuel cells will be important and depend on factors including expertise within the region and investments in RD&D. The leadership of some countries in specific areas (i.e., Japan in fuel cell technology) will shape who is interested in operating within the region.
- **Local impacts:** The extent to which projects and regional industries consider justice and equity and generate local job creation will be important. Stakeholder opposition can be a major barrier to deployment in many countries.
- **Policy landscape:** The strategic interests of a country are important to consider when evaluating the market development potential of any new industry. The hydrogen industry is developing differently in China, where the government directly supports or controls most of the industry, than in many other locations. Additionally, goals such as improving energy security, as seen in the case of the EU looking to reduce energy imports from Russia, will shape market formation. The case study regions share the goal of ultimately using hydrogen to reach decarbonization targets in hard-to-abate sectors.

- **Economic growth**: Technological innovation and leadership within areas of the hydrogen economy can drive economic growth by strengthening the international competitiveness of domestic companies.

This report seeks to bridge the information gap between stakeholders interested in hydrogen development and the future growth of clean hydrogen markets within regions. With access to information, stakeholders can better understand the industry and contribute to market development and demand formation.

Appendix: Hydrogen Market Evaluation Framework Q&A

Today's Hydrogen Industry						
	United States	**Canada**	**European Union**	**United Kingdom**	**Japan**	**China**
Current uses for hydrogen?	90% for fuel refining, ammonia, and methanol production	Mostly for refineries and chemical production	Mostly for petroleum refining, ammonia and methanol production, chemicals, other uses	90% for chemicals and refining; hydrogen is also used as a fuel, in far smaller volumes	90% of demand for oil refining; higher demand for light-duty transportation and residential heating/ power relative to rest of world	Mostly for refining and chemical production
Current hydrogen production?	11.4 Mt (2021); 76% from SMR; 23% as a byproduct of other industrial processes	3 Mt/yr, 80% from SMR	8.6 Mt/yr, 96% from natural gas and some from coal	0.5 Mt/yr, mostly from natural gas reforming	2 Mt (2020), around half from fossil gas reforming	33 Mt/yr, 63% from coal gasification
Co-location of current hydrogen demand and supply?	Yes, mostly in the Gulf Coast, California, and the industrial Midwest	Yes, mostly in British Columbia, Ontario, and Quebec	Roughly 80% of production is co-located, mostly in industrial hubs in Northwest Europe	Yes, in industrial facilities	Yes, also imports some hydrogen today	Yes, mostly in eastern coastal industrial hubs
Existence of hydrogen transport, distribution, and storage infrastructure?	1,600 miles of hydrogen pipelines; 4 underground storage facilities in use or development – 3 of which are in the Gulf Coast	91 miles of hydrogen pipelines	Almost 1,000 miles of hydrogen pipelines, 95% in Northwest Europe	25 miles of hydrogen pipelines	No hydrogen pipelines	62 miles of hydrogen pipelines
Existence of infrastructure	Extensive natural gas	Large natural gas pipeline	Extensive natural gas	Natural gas infrastructure	13 ammonia and	Extensive natural gas

that could be converted to hydrogen.	pipeline network	network (integration with U.S. markets)	pipeline network, including connections with Northern Africa; 24 ammonia and 17 methanol terminals	connected to 85% of buildings	methanol terminals	pipeline network
Structuring of energy and industrial sectors?	Large oil and gas companies are important players	Oil and gas sector is important	Regional variation	Considerable oil and gas expertise, onshore and offshore	Energy sector relies heavily on energy imports	SOEs dominate energy and industrial sectors
Historical engagement of the energy and hydrogen industries with local communities?	Environmental injustices have been prevalent in energy projects	Native communities have faced many environmental injustices through energy projects	The Energy Communities Repository and the Rural Energy Community Advisory help communities engage with clean energy projects	Environmental injustices near energy/ industrial projects	Japan opened a hydrogen museum to engage citizens with hydrogen and its applications	Companies have few incentives to engage with communities because government takes on many of the risks of energy projects

Regional Interest and Support

	United States	Canada	European Union	United Kingdom	Japan	China
National and/or regional decarbonization plan?	Net-zero target by 2050	Net-zero target by 2050	Net-zero by 2050, 55% reductions by 2035, country-level plans	78% GHG emissions reduction by 2035 and net-zero by 2050	Net-zero by 2030	Net-zero by 2060
National and/or regional clean hydrogen strategy?	Yes	Yes, and many regional government plans	Yes	Yes	Yes	Yes, and many provincial policies
Existing regulations for clean hydrogen?	3 clean hydrogen standards; blending ratios being tested	Clean hydrogen standard and a focus on integrating	Clean hydrogen standards; blending up to 5%	Clean hydrogen standard, developing a certification program;	Clean hydrogen standard	Clean hydrogen standard

		EU's CertifHy for hydrogen exports		decisions on hydrogen blending pending safety assessment		
Active policy incentives for clean hydrogen?	Production tax credit; cost reduction targets; federal funding; federal loan support	Clean Hydrogen Investment Tax Credit and CCS Tax Credits; federal funding	Federal funding; CfD mechanism	Federal funding; CfD mechanism; UK Infrastructure Bank	Cost reduction targets; federal funding; GX Economy Transition Bonds; potential use of a CfD mechanism	Central government and provincial funding
Public statements available?	Several public and private statements in support of hydrogen developmen t	Several public and private statements in support of hydrogen developmen t	Several public and private statements in support of hydrogen developmen t	Several public and private statements in support of hydrogen development	Several public and private statements in support of hydrogen developmen t	Several public and private statements in support of hydrogen development
Plans to expand clean hydrogen use?	374 publicly announced hydrogen projects as of August 2022	Several projects across the country, including for export markets	Varies by region; countries like Italy and Spain focus on green hydrogen only	25 major ongoing clean hydrogen projects	Hydrogen hub developmen t in port areas due to a high reliance on imports	Varies by province; 120 green hydrogen demonstratio n projects
Local communities' views on clean hydrogen?	Varies based on knowledge, influences, and historical factors; safety concerns exist	Potential benefits in colder climates for communities ; engagement with native communities is a policy priority	Varies by country; lack of public knowledge of hydrogen in Germany and the Netherlands and few public engagemen t projects; distrust of industry is a barrier	Environment al justice concerns for housing development s near industrialized areas	Governmen t is working to increase public knowledge about hydrogen's applications and potential	Little community engagement; improvement of air quality near industrial sites is important

Untapped Growth Potential						
	United States	**Canada**	**European Union**	**United Kingdom**	**Japan**	**China**
Clean hydrogen production inputs?	Natural gas and renewables, varying by region	Significant feedstocks for green hydrogen, natural gas, and CO_2 storage potential	Renewables in the Iberian Peninsula, potential for CCUS-enabled hydrogen projects in Northwest Europe	Large offshore wind industry	Expensive renewable generation; government investing in importing hydrogen	Significant renewable energy capacity; water scarcity in some regions; co-location of potential CO_2 storage near current hubs
Potential demand for clean hydrogen in end-use market sectors?	Focus on difficult-to-decarbonize sectors	Focus on difficult-to-decarbonize sectors	Focus on difficult-to-decarbonize sectors; demand will outstrip supply (will need to import)	Besides difficult-to-decarbonize sectors, use in the heating sector depends on feasibility of utilizing existing gas network	Government has prioritized uses in light-duty transportation and power generation; starting to focus more on industrial applications	High demand in industrial applications and heavy-duty transportation
To what extent can existing end-use assets be converted to clean hydrogen?	Pipeline standards under development	Conducting studies to blend hydrogen into natural gas pipelines in colder regions where heat pumps do not fare as well	European Hydrogen Backbone intends to repurpose natural gas pipelines and LNG terminals	Assessing safety of blending up to 20% in natural gas pipelines	Planning to use ammonia for power generation to avoid stranded asset risk of coal power plants	Lack of technical and design standards for hydrogen pipelines is a barrier
Supply chain expansion ?	Strength in electrolyzer manufacturin g	Fuel cell and PEM electrolyzer manufacturin g expertise	Strong public support for the hydrogen value chain, including developmen t of electrolyzer s	Strength in electrolyzer manufacturin g	Fuel cell and electrolyzer technology and manufacturin g strengths	AKT electrolyzer manufacturin g expertise
Needed human and knowledge	Many institutions (i.e., universities,	Many universities and research institutions	Germany is a leader in RD&D	Leading universities support the	Technologica l expertise is an asset that can be	National Key R&D Programs funding

resources ?	national laboratories) can support skills development	leading R&D efforts		hydrogen value chain	leveraged domestically and internationally	researching institutions
Transition of the current workforce ?	44% of workforce in at-risk sectors well suited for hydrogen industry	Well suited due to oil and gas expertise	Expertise in energy, particularly in Northwest Europe	Engineering employs 5.6M workers; policies to transition workers/build skills	Some regions (e.g., Tokai) have high numbers in the vehicle manufacturing sector; others (e.g., Tohoku) have construction experience	The domestic scale of manufacturing expertise is an asset
Availability of public and private support for RD&D?	Venture capital and private equity interest rising; public and private RD&D funding	Public support and national and international collaboration are core to the government's strategy	Global leader in hydrogen patents	Substantial public RD&D funding; large-scale pilot projects to inform decision-making	Robust funding for RDD&D	China's R&D spending on hydrogen is larger than that of Europe and U.S. combined.

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