The Future of Clean Hydrogen in the United States:

Views from Industry, Market Innovators, and Investors

ENERGY FUTURES
INITIATIVE

Part of the EFI Report Series
From Kilograms to Gigatons: Pathways for Hydrogen
Market Formation in the United States

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ABOUT THE ENERGY FUTURES INITIATIVE

The Energy Futures Initiative (EFI) advances technically grounded solutions to the climate crisis through science-based analysis, thought leadership, and coalition-building. Under the leadership of Ernest J. Moniz, the 13th U.S. Secretary of Energy, EFI conducts rigorous research to accelerate the transition to a low-carbon economy through innovation in technology, policy, and business models. EFI maintains editorial independence from its public and private sponsors. EFI's reports are available for download at www.energyfuturesinitiative.org

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Executive Summary

As made clear in the Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report, the global economy must reach net-zero emissions in less than 30 years to stabilize the environment and avoid the most serious impacts of climate change.[1] The United States pledged to reduce emissions by 50 to 52 percent by 2030 relative to 2005 and aspires to reach economy-wide net-zero emissions by 2050.[2] Reaching net-zero will require not only deep decarbonization of the electricity sector but also large scale deployment of a low-carbon "fuel" that can address hard-to-decarbonize sectors such as heavy transportation and industry.

Research by the Energy Futures Initiative (EFI) has identified the significant value of innovation in policy, technology, and business to accelerate the low carbon transition.[a] Hydrogen is increasingly seen as a promising pathway for the economy-wide energy transition. This promise is recognized by governments, analysts, and businesses. In particular, many companies are exploring business models and starting demonstration projects all along the hydrogen value chain.

This report, *The Future of Clean Hydrogen in the United States: Views from Industry, Market Innovators, and Investors*, sheds light on the rapidly evolving hydrogen market based on 72 exploratory interviews with organizations across the current and emerging hydrogen value chain. This report is part of a series, *From Kilograms to Gigatons: Pathways for Hydrogen Market Formation in the United States*, which will build on this study to evaluate policy opportunities for further hydrogen development in the United States.

The goal of the interviews was to provide a snapshot of the clean hydrogen investment environment and better understand organizations' market outlook, investment rationale, and areas of interest. This interview approach was supported by traditional research methods to contextualize and enrich the qualitative findings. This report should be understood as input to a more extensive EFI analysis of hydrogen market formation in the United States; the directions that companies are pursuing in hydrogen production, transport and storage, and end use at this early stage of value chain development will inform subsequent analysis in important ways.

Figure ES1 is a high-level synthesis of major cross-cutting and value chain-specific findings that emerged from the interviews.

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[a] See the EFI website for a full listing of previous reports: https://energyfuturesinitiative.org/efi-reports

Figure ES1: **Hydrogen Industry Findings: Views from Industry, Market Innovators, and Investors**

CROSS-CUTTING

- Unique diversity of companies are making investments
- Partnerships are helping firms move up the learning curve
- Favorable policy environment is emerging
- Repurposing infrastructure is a near-term priority investment strategy
- Regional hubs are a major area of focus for investors

PRODUCTION

Pathways to produce hydrogen

- Factors beyond cost can shape investor interest
- Production is most active value chain segment
- U.S. resources are seen as capable of sustaining a large market
- Incumbent producers are eyeing new growth markets
- Non-traditional firms are experimenting with various production pathways

TRANSPORT AND STORAGE

Between production and end use

- Trucking remains a primary transport option
- Regulatory environment is limiting new pipeline investment• Blending in natural gas pipelines is a major focus
- Interest in both liquid and gas forms of delivery exists
- Large-scale storage is not a major investor focus

END USE

Industries that use hydrogen

- On-road mobility is the largest near-term demand driver
- Electricity producers are experimenting with hydrogen-ready turbines
- Industrial uses may have large upside long-term
- Aviation and marine use is driven by international policies

This figure shows the major cross-cutting and value chain-specific findings that emerged from 72 exploratory interviews with organizations across the current and emerging hydrogen value chain, including production, transport and storage, and end use.

DESCRIPTION OF THE INTERVIEW PROCESS

EFI conducted interviews between April and July 2021 with 72 organizations (totaling over 50 hours) from across the current and emerging value chain for hydrogen production, transport and storage, and end use. Organizations included private companies, investors, trade groups, state and local governments, and research organizations actively engaged in hydrogen activities in the United States. Except for heavy industry and mobility, hydrogen demand for all applications is nearly nonexistent today, with different anticipated growth rates through 2050.

The interviews addressed three high-level questions:

- How does each organization view the hydrogen market in the United States today and in the future?
- Where applicable, what is each company's specific value proposition and supporting business model for hydrogen?
- What does each organization see as the priority factors (enablers and deterrents) driving business decisions in clean hydrogen?

The interviews provided value chain-specific and cross-cutting findings. Value chain-specific findings comprise the key findings within production, transport and storage, and end use. These findings provide depth into the specific areas of interest within and potentially between value chain segments. The cross-cutting findings reveal themes that were perceived to be common across most of the hydrogen activities in the United States. Collectively, these findings provide valuable perspective around the questions: what is happening and why in the emerging clean hydrogen economy. Further description of the interview process is in Appendix A.

The views of the representatives interviewed as part of this study should not be extended to those not interviewed. However, the views of the interviewees provide valuable insight into the extent to which hydrogen may be employed as a decarbonization strategy.

FINDINGS FROM INDUSTRY INTERVIEWS

The diversity of organizations interviewed for this study precludes categorical conclusions or unanimous positions. However, common themes and shared perspectives did become clear. This section provides a summary of those themes and perspectives emerging from the more than 50 hours of exploratory interviews, with supporting material from traditional research methods. Whether anticipated or unexpected, the interview responses are important for revealing how early commitments are being made, often in a proprietary context, for a hydrogen value chain that remains very fluid.

The primary motivation for the growing interest in hydrogen across a range of industry players, innovators, and investors is its potential role in decarbonization—and in some cases its potential to achieve net-zero emissions economy-wide.

Targets for rapid emissions reduction set by companies and countries has encouraged interest in hydrogen. To meet these bold targets, companies see it as critical that new investments both accelerate the deployment of existing clean solutions and fund potentially game-changing breakthroughs that can drive toward the midcentury net-zero economy-wide target. According to both incumbents and new market entrants, hydrogen appears uniquely suited to do both, lowering the carbon intensity of the existing energy system and becoming a pillar of the future low-carbon economy.

There is broad-based interest in developing hydrogen technologies across nearly every sector of the economy.

In addition to meeting internal or external emissions reduction targets, incumbent and emerging companies active in clean hydrogen are hoping to establish a foothold in what they see as a clean energy growth market. Companies as varied as data center owners, fertilizer producers, cement makers, power plant turbine manufacturers, transit agencies, and traditional oil and gas companies are exploring hydrogen applications internally while seeking more ambitious projects, often through partnerships.

There is a commonly expressed view toward a stepwise development path for exploring hydrogen technologies.

Despite the diversity of industries and their respective experience with hydrogen, there emerged a set of common milestones on the path to participate in clean hydrogen markets (Figure ES2).

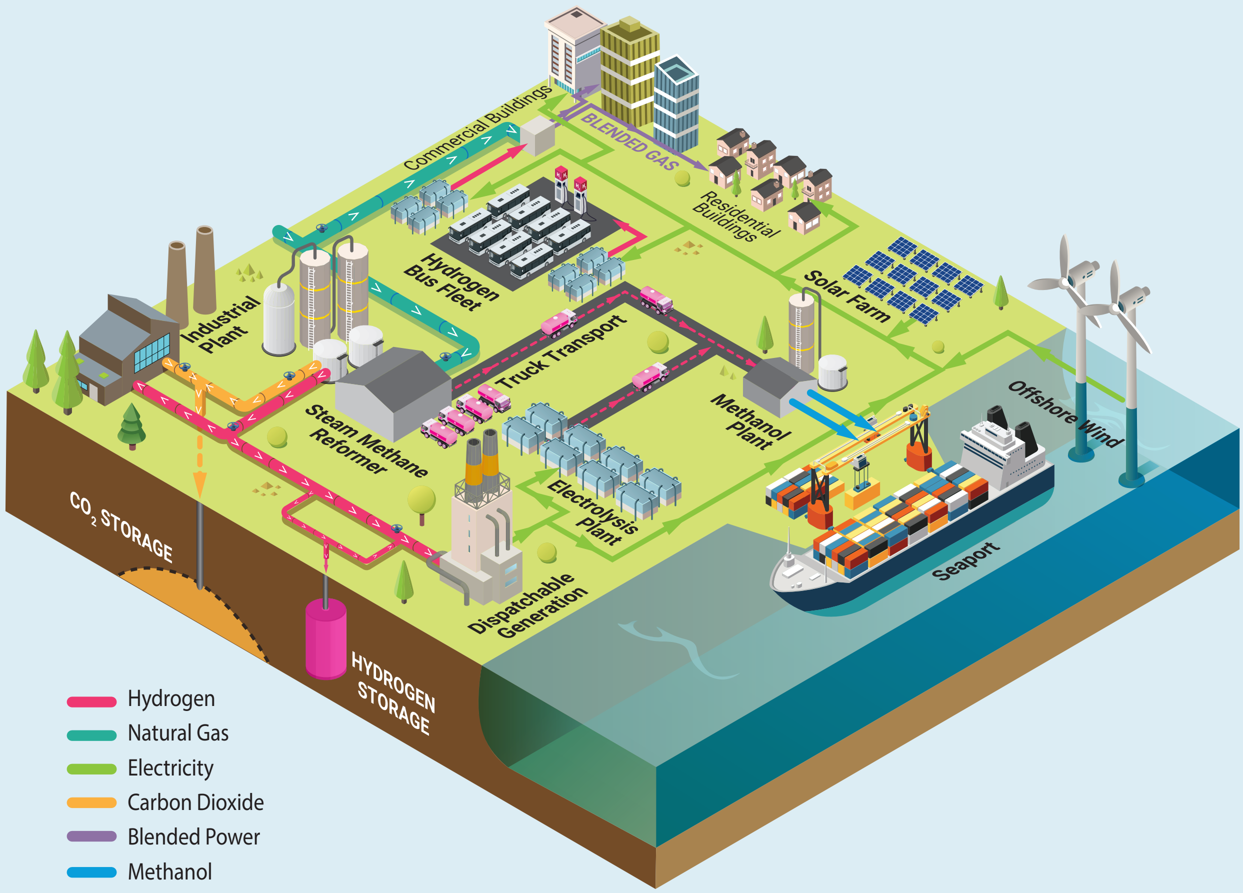
Figure ES2: Common Milestones on Companies' Paths to Hydrogen Market Participation

While interviewed companies differed in their progress along the path to market participation, many discussed common milestones. The process tends to begin by establishing emissions reduction goals. Fewer companies have reached later milestones.

There is significant interest in the potential for hydrogen to play multiple roles in decarbonization and firms see significant opportunities for localized shared infrastructure and hydrogen hub development.

In the case of industrial producers of cement, steel, glass, and ammonia—and other companies with high process heat requirements—hydrogen is seen as a necessary tool to help meet decarbonization ambitions. Figure ES3 is a notional hydrogen hub that depicts many of the uses for hydrogen under consideration from a range of industries.

Figure ES3: Hydrogen Economy Integration Across Multiple Sectors and Production Pathways

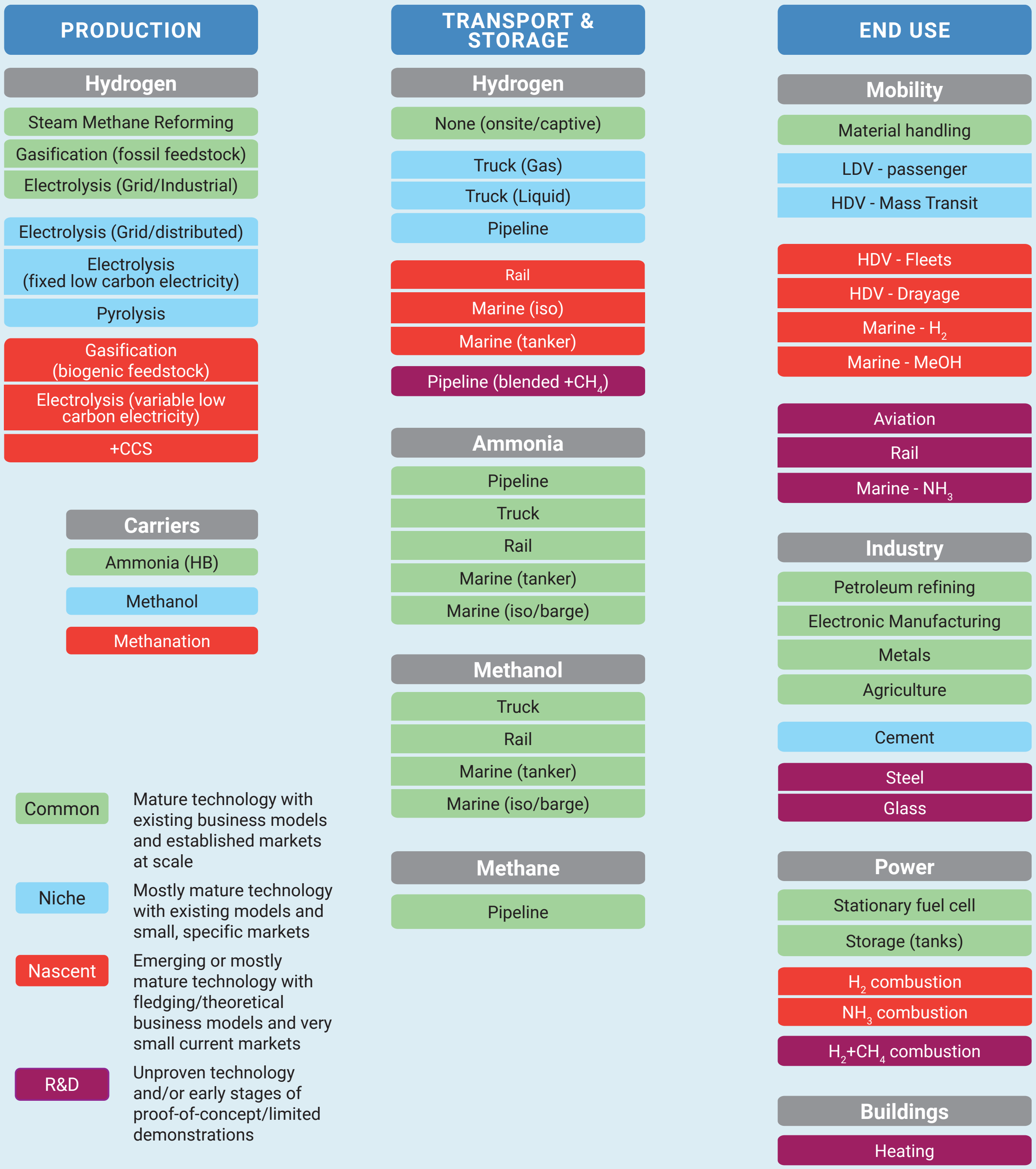


A regional hydrogen hub can provide pathways to decarbonize multiple sectors and use multiple production and transport pathways. In this example, hydrogen is produced by a steam methane reformer that uses carbon capture and several electrolysis facilities. Hydrogen is transported by both pipe and truck and used in the industrial, electric power, mobility, buildings, and shipping sectors. Electrolysis facilities use power from the bulk power supply as well as dedicated renewable resources.

The most active area of interest for investment across the hydrogen value chain is production. Companies of various sizes and levels of experience with hydrogen reported that they are exploring possibilities for hydrogen production technologies to gain operational experience for incorporation into commercial business model planning. Most interviews touched on the dual challenge of hydrogen production: reaching low costs (at scale) while emitting little to no carbon dioxide. Relative to other parts of the hydrogen value chain, the investment required to engage in initial small-scale production (most likely “green” hydrogen that can then be scaled) is relatively small. Other forms of hydrogen (e.g., “blue” hydrogen), pipeline infrastructure, and large-scale storage, for example, are relatively more expensive and face numerous financial and regulatory hurdles, while potential industrial uses like steelmaking can require costly retooling of assets that are not at the end of the lifetime.

The capability gap between today’s hydrogen producers and companies looking to enter the market appears to be significant, though some firms see this as an opportunity, while others see this as a challenge. The current hydrogen market is geographically concentrated and dominated by a few producing and consuming sectors. Oil refineries are at the heart of the U.S. hydrogen market today, as both major producers and consumers. Today, 170 facilities across the country produce 11.4 Mt of hydrogen, primarily in the U.S. Gulf Coast, California, and the upper Midwest.[3,4] Interest from firms with only marginal experience with hydrogen is growing rapidly; these new entrants are from industries including power generation, glass making, aviation, shipping, and commercial and residential heating. Figure ES4 shows the existing U.S. hydrogen value chain and the many emerging applications for production, transport and storage, and end use.

Figure ES4: Existing and Emerging Hydrogen Value Chain



PRODUCTION

Hydrogen
- 🟩 Steam Methane Reforming
- 🟩 Gasification (fossil feedstock)
- 🟩 Electrolysis (Grid/Industrial)
- 🟦 Electrolysis (Grid/distributed)
- 🟦 Electrolysis (fixed low carbon electricity)
- 🟦 Pyrolysis
- 🟥 Gasification (biogenic feedstock)
- 🟥 Electrolysis (variable low carbon electricity)
- 🟥 +CCS

Carriers
- 🟩 Ammonia (HB)
- 🟦 Methanol
- 🟥 Methanation

TRANSPORT & STORAGE

Hydrogen
- 🟩 None (onsite/captive)
- 🟦 Truck (Gas)
- 🟦 Truck (Liquid)
- 🟦 Pipeline
- 🟥 Rail
- 🟥 Marine (iso)
- 🟥 Marine (tanker)
- 🟪 Pipeline (blended +CH_4)

Ammonia
- 🟩 Pipeline
- 🟩 Truck
- 🟩 Rail
- 🟩 Marine (tanker)
- 🟩 Marine (iso/barge)

Methanol
- 🟩 Truck
- 🟩 Rail
- 🟩 Marine (tanker)
- 🟩 Marine (iso/barge)

Methane
- 🟩 Pipeline

END USE

Mobility
- 🟩 Material handling
- 🟦 LDV - passenger
- 🟦 HDV - Mass Transit
- 🟥 HDV - Fleets
- 🟥 HDV - Drayage
- 🟥 Marine - H_2
- 🟥 Marine - MeOH
- 🟪 Aviation
- 🟪 Rail
- 🟪 Marine - NH_3

Industry
- 🟩 Petroleum refining
- 🟩 Electronic Manufacturing
- 🟩 Metals
- 🟩 Agriculture
- 🟦 Cement
- 🟪 Steel
- 🟪 Glass

Power
- 🟩 Stationary fuel cell
- 🟩 Storage (tanks)
- 🟥 H_2 combustion
- 🟥 NH_3 combustion
- 🟪 H_2+CH_4 combustion

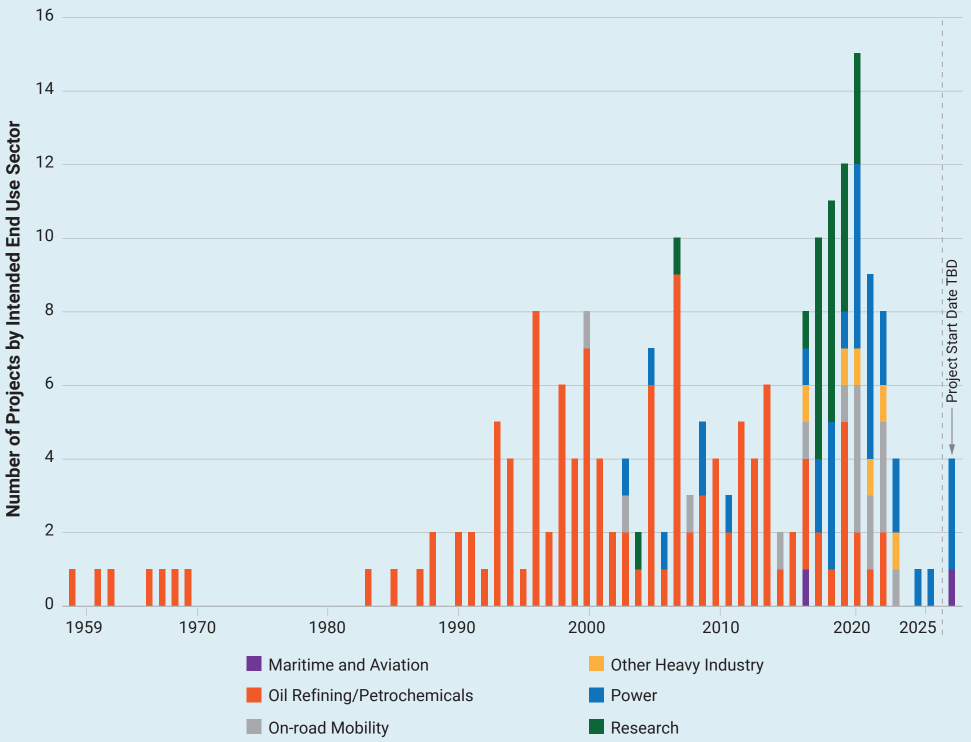
Buildings
- 🟪 Heating

🟩 Common	Mature technology with existing business models and established markets at scale
🟦 Niche	Mostly mature technology with existing models and small, specific markets
🟥 Nascent	Emerging or mostly mature technology with fledging/theoretical business models and very small current markets
🟪 R&D	Unproven technology and/or early stages of proof-of-concept/limited demonstrations

The hydrogen value chain includes common, niche, nascent, and emerging methods for production, transport and storage, and end use. Emerging value chains can connect typical production methods with novel end uses, new production methods with common end uses, or any new combination across the value chain.

Many firms are developing strategies to repurpose existing assets to use hydrogen, helping them move more quickly up the learning curve and lower the costs of participating in the clean hydrogen market. Opportunities to repurpose existing assets is a rationale cited by incumbent firms and new entrants alike, resulting in several new hydrogen projects from a range of industries. This is supported by public sources (Figure ES5). Firms are evaluating their internal engineering and project development capabilities for relevance to hydrogen projects and identifying useful existing resources (e.g., human capital, physical assets, industry market structure). Infrastructure reuse strategies are under active consideration across the entire production, transport and storage, and end use value chain. For example, owners of existing hydrogen production facilities are exploring options for lowering the carbon intensity of their product using carbon capture or renewable natural gas (RNG) (refined biogas used in place of conventional natural gas) as a feedstock. Blending hydrogen with natural gas in pipelines and turbines is another prominent infrastructure reuse opportunity with widely reported benefits, such as rapidly lowering the carbon intensity of the delivered product, and technical challenges including pipe embrittlement.[5]

Figure ES5: Number of Hydrogen Projects by Intended End Use Sector in the United States



The quantity of hydrogen projects, both operational and planned, has typically grown from 1959 through 2026 and the categories of projects by industry application has become more diverse. "Projects" is defined as publicly announced projects that use or produce hydrogen in the United States. There are 203 projects identified in this figure. Research projects that specify the intended end use of the research were placed in the corresponding category; otherwise, research projects were categorized as "Research." Note: the right-most column tallies announced projects without a set start date.

Most firms agreed that blue hydrogen is a "front runner" technology for scaling up hydrogen in the near term, though few interviewees are actively involved.

Interviewees often cited the maturity of the carbon capture technologies, the cost relative to other hydrogen production options, the existence of the Section 45Q tax credit and, in some cases, access to California's Low Carbon Fuel Standard (LCFS), as reasons why blue hydrogen is seen as a potential early mover. However, few interviewees are actively involved in the development of blue hydrogen projects and routinely noted four areas of concern: 1) the rules governing compliance for the 45Q tax credit remained unclear until very recently, and there is potential for additional policy support for alternative hydrogen production pathways or for carbon capture through the SCALE Act[b] and CATCH Act;[c] 2) the difficulty of building carbon capture at a pilot project scale; 3) the high capital costs of blue hydrogen production facilities; and 4) the potential for public and policymaker sentiment to create a disadvantaged policy and/or market environment.

Most firms see the United States as a market with high potential for large-scale growth of hydrogen.

The country's natural resources, energy infrastructure, innovation ecosystems, and technology expertise contribute to this optimistic view. While the United States currently accounts for 15 percent of global hydrogen production, there are sufficient energy resources to support several low-carbon hydrogen production pathways at scale.[6] In some regions, renewable energy resources offer abundant, zero-carbon electricity generation needed for electrolysis. Natural gas is available in most parts of the country as a low-cost feedstock for steam methane reformation (SMR) and other production techniques (e.g., methane pyrolysis). Nuclear generation and RNG may also be available for zero-carbon hydrogen production in some places. The geology in many regions of the country is well suited to carbon dioxide storage—enabling carbon capture for SMR production—and some locations offer underground salt caverns ideal for hydrogen storage.

Many firms see current demonstration projects in Europe as informing clean hydrogen opportunities, practicalities, economics, and business arrangements in the United States.

Domestic industrial firms that face costly and uncertain retrofit requirements for moving to clean hydrogen processes highlighted the value of allowing European projects to test the real-life performance of alternative processes and equipment. Many of those European projects are supported by government funding on a scale not available in the United States today. Companies are also observing emerging business models, including those oriented around hub formation in Europe and Asia—projects that are also receiving generous government support.[7,8]

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[b] The 2021 *Storing CO_2 and Lowering Emissions (SCALE) Act*, sponsored by Sen. Chris Coons (D-DE) in the Senate and Rep. Marc Veasey [D-TX] in the House would provide DOE cost sharing for commercial CO_2 storage hubs and establish programs to finance shared CO_2 transport infrastructure.

[c] The 2021 *Coordinated Action to Capture Harmful (CATCH) Emissions Act*, proposed by Rep. Tim Ryan (D-OH), would increase tax credit levels for carbon capture from industrial facilities and power plants.

Many firms are exploring a wide range of collaborative partnerships that would increase their knowledge of hydrogen.

Companies see the nascency of new supply and demand pathways as opportunities to expand beyond their organizational boundaries. According to public sources, energy utilities, for example, are working collaboratively with the Department of Energy's National Labs, universities, and industry associations such as the Gas Technology Institute (GTI), the Electric Power Research Institute (EPRI), and the Pipeline Research Council International (PRCI).[9,10,11,12] Through these activities, organizations are broadening capabilities, developing best practices, and sharing lessons learned.

Many firms viewed on-road mobility as the most mature near-term demand growth area for hydrogen in the United States.

There are more policies supporting hydrogen's use in the mobility sector than for any other application. Light-duty vehicles and forklifts that run on hydrogen are already commercially available, and several companies are offering heavy-duty vehicles in the near term. While there is obvious competition with battery electric vehicles (BEVs), there is optimism from the interviewees that hydrogen vehicles may offer strong alternatives, especially for medium- and heavy-duty vehicle classes. Concerns about overreliance on the electric grid, especially for emergency response vehicles needed for power restoration during outages, are also shaping some investment decisions.

Other end uses, including heavy industry, power generation, aviation, and maritime mobility, are seen as medium- and long-term prospects for large-scale hydrogen demand.

Industrial end-users such as cement, steel, and glass broadly see hydrogen as a potential pathway to decarbonize. However, many domestic heavy industries reported few immediate actions to retool their processes or pay a premium for lower-carbon sources of hydrogen to meet their current energy and chemical requirements. In power generation, many of the major turbine manufacturers have, or are developing, units that can be co-fired with hydrogen. Some power producers are in pilot stages to experiment with using hydrogen in existing plants or develop new, hydrogen-ready facilities. Finally, aviation and maritime transport companies are progressing slowly in hydrogen development, largely due to long engineering timelines and slow stock turnover. Commercial aviation and shipping companies are actively exploring options to reduce emissions—usually low carbon fuel, electric, and hydrogen—considering the cost, storage, and safety requirements.

Recent policy support is motivating significant interest in developing hydrogen projects, especially regional hubs.

The $1.2 trillion Infrastructure Investment and Jobs Act includes $8 billion over five years for developing four hydrogen hubs, two of which are to be in natural gas-producing regions. The bill requires that hubs demonstrate a range of production pathways, including one each relying on fossil fuels, renewable energy, and nuclear power. The legislation also prescribes specific end uses that must be demonstrated at one or more hubs: electric power, industrial use, residential and commercial heating, and mobility. The Biden Administration's American Jobs Plan (AJP) also includes substantial support for hydrogen, including support for a production tax credit for 15 clean hydrogen demonstration projects and $15 billion for research and development (R&D) related to hydrogen and carbon capture and sequestration (CCS).[13]

The findings derived from EFI's 72 exploratory interviews show that there is significant and growing interest across a wide array of organizations in clean hydrogen as a decarbonization pathway for the United States. Much of this interest stems from company and government emissions reduction targets. Still, today's carbon-intensive energy system is enormous, complex, and historically slow to change, and organizations remain uncertain as to how, where, and why clean hydrogen markets will emerge.

Bridging this gap between enthusiasm for clean hydrogen to support emission reduction goals and the realities of complex energy systems requires policy activity to unlock the latent potential of private companies, investors, trade groups, government entities, and research organizations in achieving a clean energy future. In conclusion, a coordinated set of federal and state policies, regulations, and incentives would elicit a strong response from the private sector and create a major opportunity to accelerate U.S. hydrogen market formation.

Framing the Renewed Focus on Hydrogen

This report sheds light on the rapidly evolving hydrogen market based on 72 exploratory interviews with organizations across the current and emerging hydrogen value chain. The interviews provide an understanding of organizations' market outlook, investment rationale, and areas of interest. This section of the report, based on non-interview research, provides key framing and context for the interview findings that follow.

The world has reached an inflection point in its efforts to address the climate crisis. The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report was explicit: the global economy must reach net zero emissions in less than 30 years to avoid the most serious impacts of climate change.[14]

Most nations of the world are now grappling with the need to rapidly adjust their post-Paris climate mitigation plans to accommodate net-zero emissions targets by midcentury—and the United States is no exception. Under President Biden's leadership, the United States has pledged to reduce emissions by 50-52 percent by 2030 relative to 2005 and has set an aspiration to reach net-zero by 2050.[15] Reaching these targets requires enormous investments in clean energy alternatives to fossil fuels.

At the same time, nations committed to meeting net zero targets must address the inherent difficulties of doing so. Energy systems are almost as large as the need to rapidly change them. These systems have evolved incrementally due to their size, costs, value, and complex market and regulatory structures. This slow pace of change reflects a level of regulatory attention that underscores the essential services that energy systems provide—and must continue to provide—to all levels of society.

The need for rapid, system-wide emissions reductions may be hardest for those sectors whose emissions are most difficult to abate, such as industry. This sector is critically important to local, regional, and national economies, yet there are few options for rapidly reducing its emissions. Absent new and scalable technologies, industry requirements for high quality and high availability process heat point to the ongoing need for a fuel for the foreseeable future. Also, there is the urgency of climate change and the value of "early gains" in emissions reductions in the near- to mid-term, while investments are being made in critical longer-term technology needs for meeting net-zero targets, such as carbon dioxide removal (CDR).

The clean energy transition, while critical, threatens to strand both assets and jobs; the interest in re-using and re-purposing infrastructure and skillsets is growing, as is an interest in the economies of scale that could be achieved with shared and co-located infrastructure. Historically, the energy system has benefited from fuel versatility—where the needs of multiple end-uses and users can be met using common fuels and infrastructure. At the same time, regional differences in infrastructures, mitigation options, and economies must be accommodated.

These tensions must be both managed and overcome. This has placed a renewed focus on the range of existing technology options and regional solutions needed to meet net-zero targets, both in the United States and around the world; the ease and speed at which these solutions can be widely deployed; the economic, community, and equity impacts of the clean energy transition; the need for large and accelerated investments in innovation, deployment, infrastructure, and supply chains; and new policies, and regulatory and market structures to appropriately support these needs, investments, and actions.

HYDROGEN CAN MEET A RANGE OF CRITICAL NEEDS—THOUGH STILL FACES CHALLENGES

It is little wonder, given this daunting set of challenges, requirements, and urgency, that hydrogen is once again the focus of industry, investors, and policymakers. Hydrogen addresses many of the critical challenges, roadblocks, and requirements for rapid decarbonization of critical sectors of the U.S. economy.

First, and perhaps most significant, is hydrogen's potential role in decarbonization. As noted, there is an unprecedented and urgent need for emissions reductions at very significant scale to meet mid-century targets. To meet these bold targets, it is critical that new investments both accelerate the deployment of existing clean solutions and fund prospective game-changing breakthroughs that can drive towards the midcentury net-zero target. Hydrogen is uniquely suited to both lower the carbon intensity of the existing energy system and become a pillar of the future low-carbon economy.

Currently, most of the hydrogen production and consumption in the United States today is by and for the refining industry, but organizations small and large in both the public and private sectors are developing new production pathways and use cases. The new sectors—spanning power generation, heavy industry, on-road mobility, aviation, shipping, finance and investment, vehicle manufacturing, and commercial and residential heating—are developing and repurposing assets to integrate in an expanding hydrogen economy.

Hydrogen can be combusted in a power generation turbine either as pure hydrogen or blended with natural gas. Hydrogen, via fuel cells, can support a range of mobility options. Hydrogen can be moved in tankers, via pipelines specifically built for hydrogen transport, as a blend in other pipelines up to a certain level, or in multi-purpose pipelines treated to accommodate its embrittlement characteristics. It can also act as a large-scale, long-duration energy storage medium. In short, hydrogen's flexibility and value for many industrial subsectors, and its potential as both a steppingstone and a destination for reaching net-zero emissions, is driving the current investor interest.

Hydrogen, however, has a range of issues that need to be addressed to further enable its full suite of uses and its larger role in the relatively near-term decarbonization of the U.S. economy. Hydrogen production via steam methane reforming (SMR), the least expensive and most prevalent option, emits carbon, as do the range of industrial processes that use hydrogen as a specialty chemical or feedstock. Autothermal reforming (ATR), an alternative process to produce hydrogen from natural gas or other hydrocarbons, faces similar emissions drawbacks.[16] Hydrogen production from electrolysis, while emissions-free, can be significantly more expensive than methane reforming and requires innovation to reduce its costs.

Further, current regulation of hydrogen focuses on safety. Hydrogen is priced based on its current limited uses, not on its potential for production or consumption as an energy commodity. Hydrogen tends to be produced and consumed in close proximity; as such, it has a limited distribution infrastructure. Additionally, as noted, hydrogen pipelines require special treatment to address embrittlement issues.

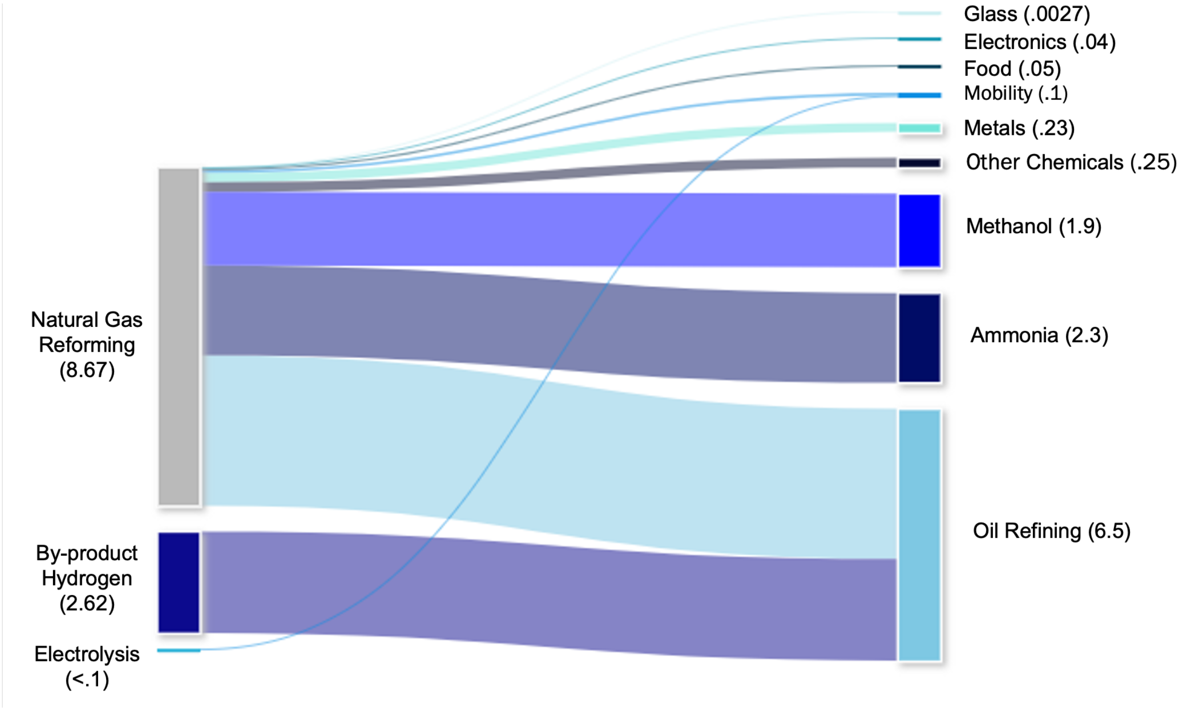
These opportunities and challenges must be addressed by policymakers, industry players, and investors. This report, *The Future of Clean Hydrogen in the United States: Views from Industry, Market Innovators, and Investors*, is part of series of EFI analyses, *From Kilograms to Gigatons: Pathways for Hydrogen Market Formation in the United States*, which will build on this study analysis to evaluate the technology and policy opportunities for unlocking the decarbonization potential of hydrogen.

HYDROGEN IN THE UNITED STATES TODAY

The use of hydrogen as a clean fuel has attracted the interest of scientists, energy experts, and policymakers in the United States for the past 70 years. While hydrogen has a low energy density per cubic meter, it has a very high energy density per kilogram, which led NASA to develop liquid hydrogen as a rocket fuel in the early 1950s. Around that time, the nuclear power industry posited that excess nuclear power could produce cheap hydrogen to displace more expensive fossil fuels.[17] By early 2003, President George W. Bush envisioned a “hydrogen economy” to strengthen energy independence and announced in his State of the Union address a commitment to hydrogen-powered automobiles. While his vision of a hydrogen economy has yet to emerge, the United States currently plays a large role in fuel cell and hydrogen technology development, commercializing a wide range of solutions that produce, deliver, store, and use hydrogen.[18]

Approximately 11.4 million metric tons (Mt) of hydrogen are produced annually in the United States, more than 15 percent of the world’s total.[19,20] Of that, approximately 77 percent comes from natural gas reforming (Figure 1), a thermal process in which hydrocarbons are used to produce hydrogen, carbon monoxide, and carbon dioxide.[21] Another 23 percent is produced as a by-product of petroleum refining and other industrial chemical processes and is typically consumed on-site.

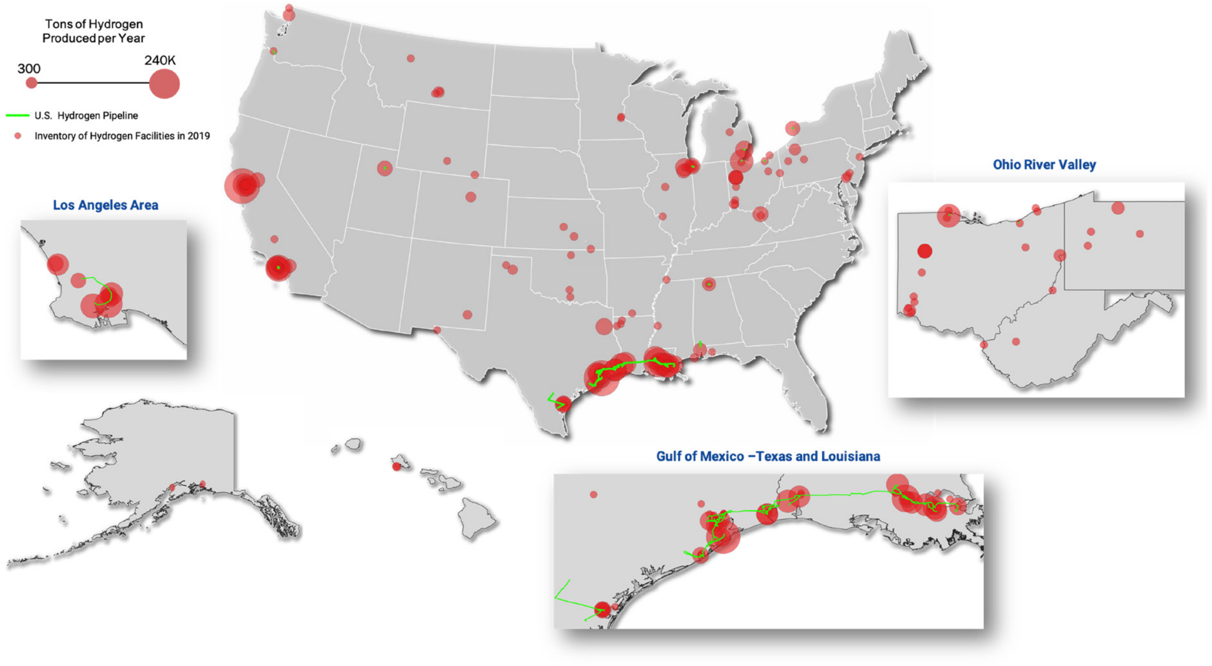
Figure 1: Current Hydrogen Supply and Demand Balance in the United States (Mt)[22,23]



Natural gas reforming makes up most of hydrogen production in the United States today, which predominantly supplies the refining industry and ammonia production. Some refineries produce hydrogen as a byproduct of other processes and consume all hydrogen produced. Hydrogen produced by electrolysis is on a small scale and mostly supplies demonstration-scale mobility end uses. Data from FCHEA, 2020 and D.R. Brown, 2016.

As of 2019, there were approximately 170 facilities in the United States producing hydrogen through methane reforming or as a by-product of the petroleum refining process (Figure 2).[24,25] About half of U.S. hydrogen is produced and consumed by the same entity (usually a refinery), while the other half comes from merchant providers who sell hydrogen to end users.

Figure 2: Current U.S. Hydrogen Production Facilities and Pipelines[26,27]



Current hydrogen production includes both facilities that create hydrogen as a byproduct and dedicated hydrogen facilities for onsite use or sale from merchant providers. Hydrogen pipelines estimated from the Pipeline and Hazardous Materials Safety Administration (PHMSA) public data viewer are shown in green. The United States currently produces 11.4 Mt of hydrogen annually. Note that this report could not identify the production capacity of many facilities and those facilities are displayed as the smallest dots on the map. Data from Environmental Protection Agency (EPA) Flight and Hydrogen Tools.

Merchant hydrogen production facilities are often located at the customer's plant, but sometimes merchants rely on pipeline or trucks for shipping.[28] There are at least 25 operating hydrogen pipelines in the United States, collectively spanning approximately 1,600 miles and almost all are in the Gulf Coast region.[29] For comparison, there are around 4,500 miles of carbon dioxide (CO_2) pipelines and 3,000,000 miles of natural gas pipelines.[30,31] Other options for transporting hydrogen that are in development include maritime and rail (Table 1). Hydrogen can also be transported via an intermediate chemical carrier like ammonia and methanol; in both cases, hydrogen must be separated from the unneeded molecules near its point of use, adding cost and efficiency penalties at the expense of potentially easier transport options in some niche applications.

Table 1: Description of Existing and Emerging Hydrogen Transport Methods

Transporting Hydrogen	**Truck (liquid)**	• An established technology for transporting hydrogen that has been liquefied in super-insulated, cryogenic tanker trucks to distribution sites; most common when high-volume transport is needed in the absence of pipelines
	Truck (gas)	• An established technology using trucks called tube trailers that carry gaseous hydrogen compressed at very high pressures in long cylinders that are stacked and hauled to distribution sites
	Pipeline	• An established technology for transporting gaseous hydrogen through a pipeline, like natural gas, which is especially common for long distance and high-volume transport
	Maritime	• A generally mature technology for transporting large volumes of hydrogen through waterways, between U.S. ports, or overseas using barges in compressed tube skid trailers or high-efficiency liquid storage containers
	Rail	• A generally mature technology for transporting liquified hydrogen in rail tank cars for bulk transport using the existing U.S. freight rail network
Hydrogen Carriers	**Ammonia**	• An established technology using ammonia in transport, which is converted, or “cracked” into nitrogen and pure hydrogen near end use • Different use case than ammonia used as a fuel itself
	Methanol	• An established technology using methanol in transport which is reformed on-site to generate hydrogen for end use applications • Different use case than methanol used as a fuel itself

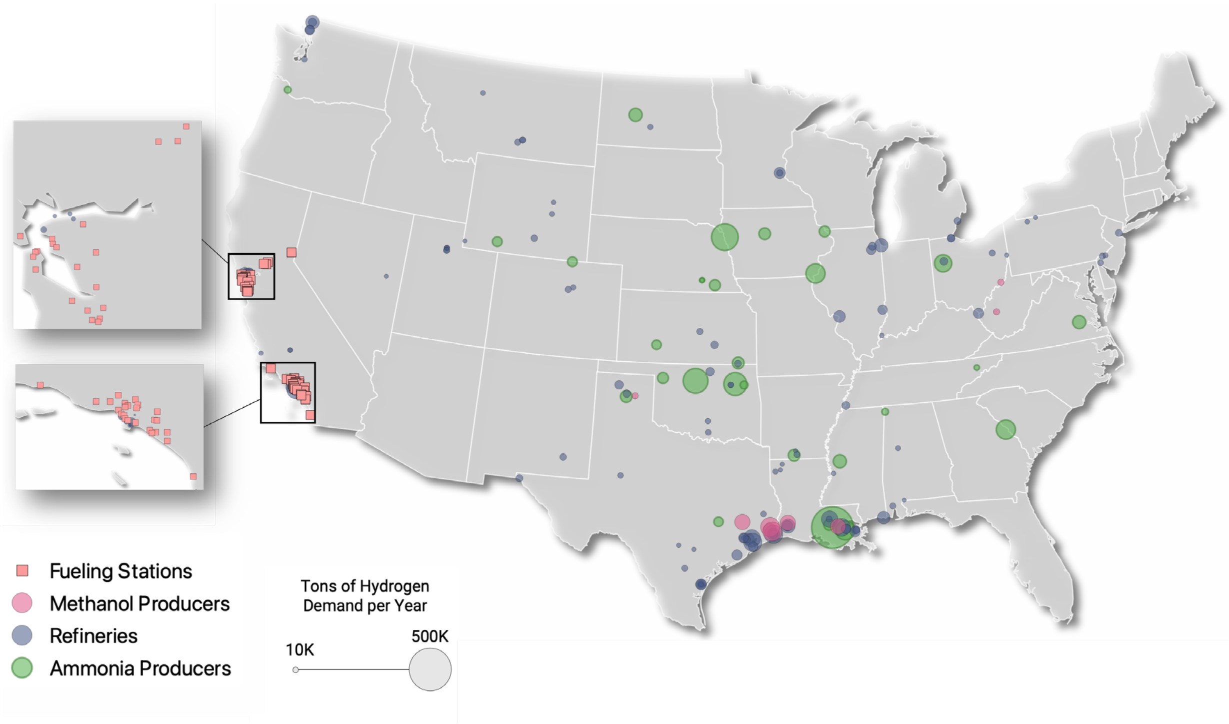
Hydrogen is used by multiple industries across the country (Figure 3). The oil refining industry is responsible for most hydrogen production and consumption in the United States today.[32] Refineries use hydrogen to reduce the sulfur content of diesel fuel. Ammonia and methanol production are the second and third highest hydrogen end uses, together with oil refining accounting for more than 85 percent of the nation’s total.

Today’s hydrogen production in the United States is almost entirely reliant on methods that produce greenhouse gases, contributing to climate change at a significant scale; large U.S. facilities emitted 44 Mt CO_2e in 2019, roughly 3 percent of the country’s total industrial emissions.[33] These totals are even higher when including the upstream natural gas system emissions associated with fueling these facilities. The opportunity for clean hydrogen to drive emissions reduction are thus two-fold: reducing emissions of existing hydrogen uses by displacing carbon-intensive production with cleaner alternatives and displacing dirtier end uses with clean hydrogen in markets currently using fossil fuels today.

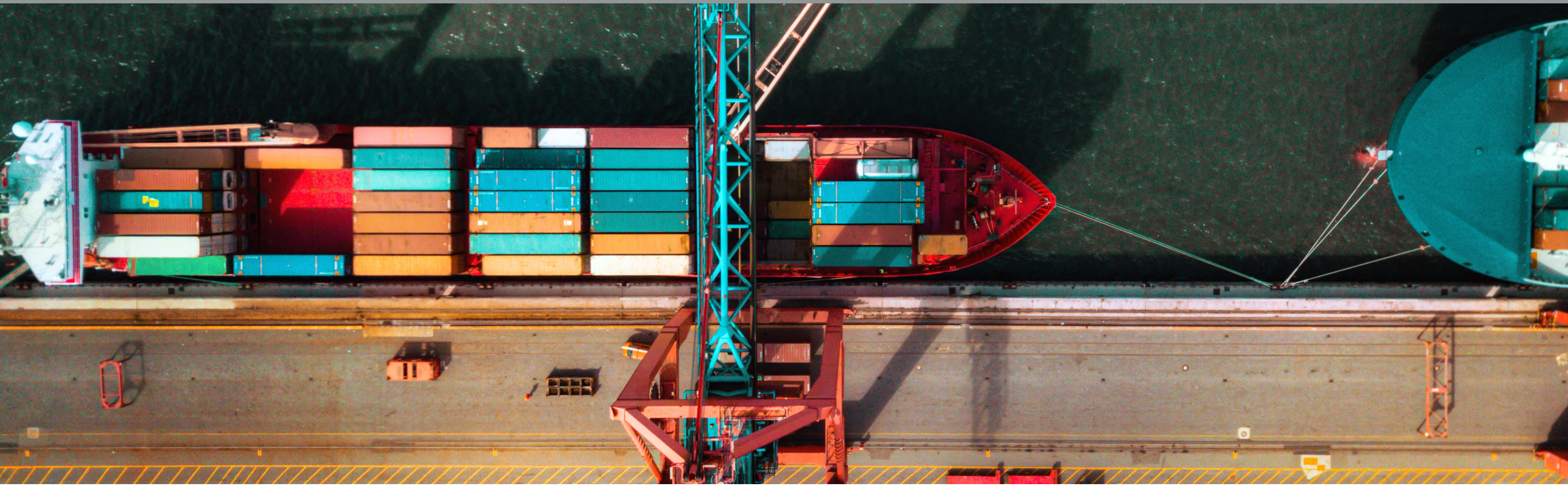
The mobility market for hydrogen is still relatively small.[34] The number of hydrogen fuel cell electric vehicles (FCEVs) remains relatively small, though roughly half the world’s total are in the United States.[35] As of 2019, there are more than 10,800 FCEVs (roughly 0.004 percent of the U.S. vehicle stock), nearly 50 fuel cell electric buses (FCEB), and 48 hydrogen fueling stations (all but one in California).[36] In addition, there are more than 25,000 hydrogen fuel cell-powered material handling vehicles such as forklifts operating in warehouses and distribution facilities across the country.[37]

Fuel cells are also used in stationary power applications, but these primarily use natural gas and produce CO_2 emissions in most cases. As of January 2020, there were over 550 MW of installed or planned fuel cells for large-scale backup power, critical loads, and combined heating and power applications.[38] The basic design of these fuel cells is nearly identical to that of hydrogen-fueled versions because converting the natural gas to hydrogen is a necessary process step that occurs within the device. Manufacturers of stationary power applications can transition their production to hydrogen-fueled applications at relatively low cost if there is demand.

Figure 3: Existing Centers of Hydrogen Demand[39,40]



Ninety-four percent of hydrogen demand in the United States is from refineries, ammonia plants, and methanol plants. Another one percent of consumption comes from mobility. The remaining five percent of demand is attributed to metals processing, chemicals production, glass, electronics, and food manufacturing. Data from NREL and Alternative Fuels Data Center.



EMERGING ROLES FOR HYDROGEN

Today, hydrogen is used primarily as a specialty chemical or feedstock for industrial processes; however, hydrogen has the potential to serve as a decarbonization tool in major sectors of the economy, including electricity, mobility, industry, and buildings.[41,42] While the existing hydrogen market is approximately 11.4 Mt per year, the Department of Energy's (DOE) H2@ Scale initiative projects a total U.S. technical potential for hydrogen demand of approximately 106 Mt per year, dominated by industrial use and on-road mobility.[a,43]

A future clean hydrogen economy will require modified and new methods to produce, transport, store, and use hydrogen. Based on the opportunities for hydrogen use in myriad sectors, the potential future hydrogen value chain is significantly expanded from the current one (Figure 4). The emerging roles for hydrogen involve more methods of production, transport and storage, and end use, while entirely new aspects of the value chain could also be realized. Hydrogen carriers, for instance, do not exist as part of today's hydrogen market but could be a viable option to overcome challenges associated with transporting hydrogen in the future. Within established end uses like mobility, additional hydrogen use cases are emerging, such as hydrogen as an aviation fuel.

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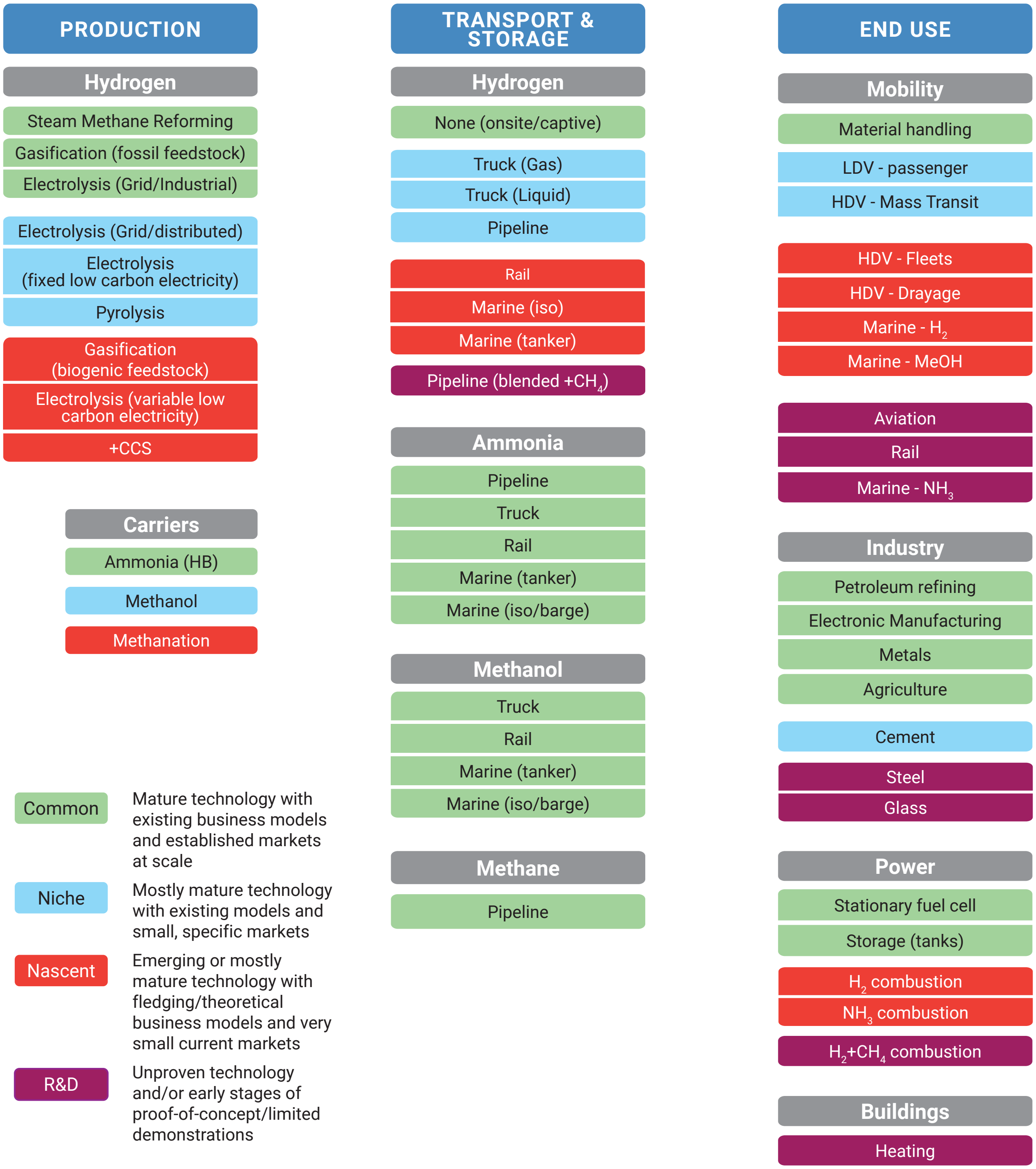
[a] The potential market for hydrogen is an upper bound estimate for the demand that could be met without considering economics.

Figure 4: Emerging and Existing Hydrogen Value Chain



PRODUCTION

Hydrogen
- 🟩 Steam Methane Reforming
- 🟩 Gasification (fossil feedstock)
- 🟩 Electrolysis (Grid/Industrial)
- 🟦 Electrolysis (Grid/distributed)
- 🟦 Electrolysis (fixed low carbon electricity)
- 🟦 Pyrolysis
- 🟥 Gasification (biogenic feedstock)
- 🟥 Electrolysis (variable low carbon electricity)
- 🟥 +CCS

Carriers
- 🟩 Ammonia (HB)
- 🟦 Methanol
- 🟥 Methanation

TRANSPORT & STORAGE

Hydrogen
- 🟩 None (onsite/captive)
- 🟦 Truck (Gas)
- 🟦 Truck (Liquid)
- 🟦 Pipeline
- 🟥 Rail
- 🟥 Marine (iso)
- 🟥 Marine (tanker)
- 🟪 Pipeline (blended +CH_4)

Ammonia
- 🟩 Pipeline
- 🟩 Truck
- 🟩 Rail
- 🟩 Marine (tanker)
- 🟩 Marine (iso/barge)

Methanol
- 🟩 Truck
- 🟩 Rail
- 🟩 Marine (tanker)
- 🟩 Marine (iso/barge)

Methane
- 🟩 Pipeline

END USE

Mobility
- 🟩 Material handling
- 🟦 LDV - passenger
- 🟦 HDV - Mass Transit
- 🟥 HDV - Fleets
- 🟥 HDV - Drayage
- 🟥 Marine - H_2
- 🟥 Marine - MeOH
- 🟪 Aviation
- 🟪 Rail
- 🟪 Marine - NH_3

Industry
- 🟩 Petroleum refining
- 🟩 Electronic Manufacturing
- 🟩 Metals
- 🟩 Agriculture
- 🟦 Cement
- 🟪 Steel
- 🟪 Glass

Power
- 🟩 Stationary fuel cell
- 🟩 Storage (tanks)
- 🟥 H_2 combustion
- 🟥 NH_3 combustion
- 🟪 H_2+CH_4 combustion

Buildings
- 🟪 Heating

🟩 Common	Mature technology with existing business models and established markets at scale
🟦 Niche	Mostly mature technology with existing models and small, specific markets
🟥 Nascent	Emerging or mostly mature technology with fledging/theoretical business models and very small current markets
🟪 R&D	Unproven technology and/or early stages of proof-of-concept/limited demonstrations

The hydrogen value chain includes common, niche, nascent, and emerging methods for production, transport and storage, and end use. Emerging value chains can connect typical production methods with novel end uses, new production methods with common end uses, or any new combination across the value chain.

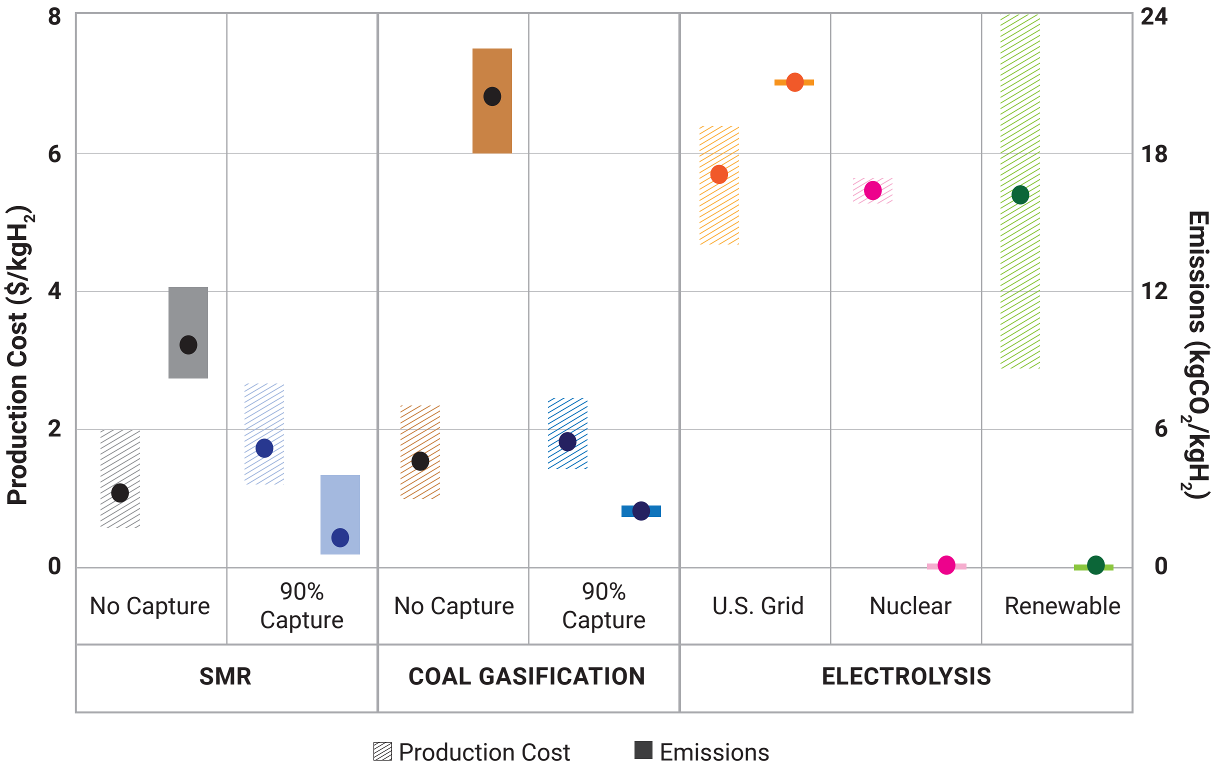
Realizing hydrogen's potential will require modified or new production methods that significantly reduce emissions compared to today's approaches (Table 2). In many cases, emissions-intensive methods of hydrogen production like natural gas reformation and coal gasification can produce clean hydrogen by procuring cleaner feedstocks, using lower-carbon power sources, or adding carbon capture capabilities. For instance, the process of gasification to produce hydrogen has traditionally employed coal, but carbonaceous waste and biomass are also viable feedstocks. Carbon capture units can be added to SMRs to reduce emissions ("blue" hydrogen) and continue the use of existing SMR facilities. Electrolysis can be powered by electricity produced by renewables or clean grid electricity rather than from fossil fuels ("green" hydrogen).

Table 2: Description of Various Hydrogen Production Pathways

Natural Gas Reforming (SMR/ATR)	• Steam Methane Reforming (SMR): An established technology where methane reacts with steam to produce hydrogen, carbon monoxide, and carbon dioxide • Autothermal Reforming (ATR): The partial oxidation of a hydrocarbon feedstock (typically natural gas) with oxygen and steam to produce syngas containing hydrogen and carbon monoxide[44]
Coal Gasification	• An established technology where coal is gasified to produce synthesis gas then hydrogen • Commercially available but not currently used in United States
Natural Gas with Carbon Capture	• A generally mature technology that captures CO_2 emissions from fossil fuels used in hydrogen production • Currently a small market with two large, at-scale projects coming online in the next one to three years[45, 46]
Electrolysis Using Renewable Energy	• A generally mature technology where water molecules are split into oxygen and hydrogen via wind or solar energy •Rapidly growing industry, with 172 MW of capacity in operation or under construction across the country[47]
Electrolysis Using Nuclear Energy	• A generally mature process that powers electrolysis with nuclear energy • Feasible market potential with ongoing basic research in the United States
Electrolysis Using Grid Electricity	• A generally mature process that powers electrolysis with grid electricity • Current source of most electrolysis in United States because dedicated renewables are more expensive
Methane Pyrolysis	• A generally mature technology where thermal splitting of methane produces hydrogen • Creates a solid carbon byproduct instead of CO_2 emissions • Two facilities scaling up designs but otherwise not common to-date
Biomass & Waste Gasification	• An emerging technology where biomass or waste is gasified to produce hydrogen • Two commercial facilities finalizing funding and permitting of their technologically advanced projects

These alternative hydrogen production methods can dramatically reduce CO_2 emissions, though at higher cost. While hydrogen produced via SMR or coal gasification typically costs around $1/kg (Figure 5), clean hydrogen production methods—including hydrogen produced by SMR or coal gasification accompanied by CCS, electrolysis using nuclear power, and electrolysis using wind or solar—emit less than five kilograms of CO_2 per kilogram of hydrogen but can cost more than $5/kg of hydrogen.[b] The DOE HydrogenShot program is focused on lowering the costs of clean hydrogen production to $2/kg by 2025 and $1/kg by 2030.[48]

Figure 5: Hydrogen Production Costs and Emissions Estimates from Literature



Costs to produce hydrogen (estimated in studies published between 2017 and 2021) may range from less than a dollar to eight dollars per kilogram, depending on production pathway and assumptions (e.g., location, year of production, utilization rates, efficiency, CO_2 transport and storage costs, and technology learning curves). Production pathways yield different levels of emissions. SMR and coal gasification production pathways can be emissions-intensive, although carbon capture can significantly reduce those emissions. Production by electrolysis can be emissions-intensive unless the electricity is produced by zero-carbon sources. Complete assumptions and sources are available in Appendix B.

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[b] The high spread of the production cost of hydrogen from electrolysis using renewable energy is due to two factors: variations in renewable electricity costs and the marginal cost of renewable electricity production often considered in many estimates is much lower than the true, total cost. Such electricity costs depend on a combination of elements such as geographic resources, financial incentives, and regulations.

Hydrogen can be used across multiple sectors of the economy (Table 3). Hydrogen is an attractive technology for some of the most challenging-to-abate sectors, such as high-temperature process heating, electricity load following, and heavy-duty trucking. In on-road mobility, hydrogen-powered fuel cell vehicles are attractive zero-emission solutions for light-duty, heavy-duty, and material-handling vehicles due to their short fueling times and large on-board energy storage capacity and could complement BEVs for decarbonizing heavier-duty cycles.[49]

Hydrogen can be used in combustion turbines to produce zero-carbon electricity, as a clean, high-capacity, long-duration storage resource, or as backup power for critical infrastructure (e.g., hospitals, data centers, and military bases).[50] Hard-to-decarbonize industrial sectors can use low-carbon hydrogen as feedstock in many industrial processes, such as steelmaking, chemical production, and refining, or as a heating source to replace fossil fuels (mainly natural gas and petroleum). There is also significant interest in blending hydrogen into the existing natural gas system to lower the carbon intensity of U.S. buildings and other end users of natural gas with minimal infrastructure deployment.

Table 3: Description of Potential Hydrogen Consumers

Mobility	• An established powertrain technology that consumes hydrogen in a fuel cell to produce electricity with water as the only byproduct • A generally mature technology in mass transit, though rail is still in the ‘proof of concept’ phase and not yet widely viable commercially • Commercial HDVs are an emerging technology with competitive advantages over battery electric vehicles in fueling times, range, and cost when the vehicle is large enough
Aviation	• R&D is ongoing for use of hydrogen as an airplane fuel that uses large storage tanks onboard • Similar level of R&D on the development of power systems for taxiing services and equipment carriers
Maritime	• An emerging technology focused on using low-carbon fuels to displace diesel fossil fuels used in heavy shipping
Steel	• R&D centered on using hydrogen as a reducing agent in blast furnaces or for direct reduction of iron (DRI) in an electric arc furnace (EAF)
Power	• An established technological process where natural gas and hydrogen are blended at the right threshold to keep gas turbines running while reducing emissions with minimal system upgrades • More R&D is required to replace natural gas with hydrogen entirely; pipelines need expensive upgrades and there are safety concerns for residential and commercial buildings
Cement	• A generally mature technology that uses hydrogen fuel (blended with natural gas or alone) in the process heating stages of cement production

This interest in clean hydrogen as a diverse decarbonization tool has garnered notable policy support, particularly via funding in recent legislation. The $1 trillion bipartisan Infrastructure Investment and Jobs Act (IIJA) would provide $8 billion over five years for developing four hydrogen hubs, two of which must be in natural gas-producing regions.[51] Box 1 shows many of the opportunities of developing hydrogen-based regional hubs. At least one hub would be required to demonstrate hydrogen production from fossil fuels, renewable energy, and nuclear power; and at least one hub needs to demonstrate hydrogen use in the electric power sector, industrial sector, residential and commercial heating, and mobility sector. The IIJA also dedicates $1 billion to hydrogen demonstration projects including storage techniques, integration with power systems, and large electrolysis facilities.

R&D for hydrogen technologies included in the IIJA would support broad, economy-wide application of clean hydrogen.[52] R&D focus areas include consumption from a variety of end uses (e.g., mobility, power, industrial, residential), production from several pathways (e.g., using fossil fuels with CCS, using nuclear energy, using renewable energy), and various modes of transport (e.g., using an energy carrier like methanol, repurposing pipelines, and blending hydrogen into natural gas pipelines). The IIJA will also direct the Department of Energy (DOE) to develop a national clean hydrogen strategy and roadmap.

Further, President Biden’s policy agenda for climate and energy, the American Jobs Plan (AJP), also includes substantial support for hydrogen. Large components of the AJP not included in IIJA are expected to be in a more comprehensive bill to be passed in budget reconciliation legislation. The AJP called for a production tax credit for 15 clean hydrogen demonstration projects and $15 billion for hydrogen and CCS R&D.[53]

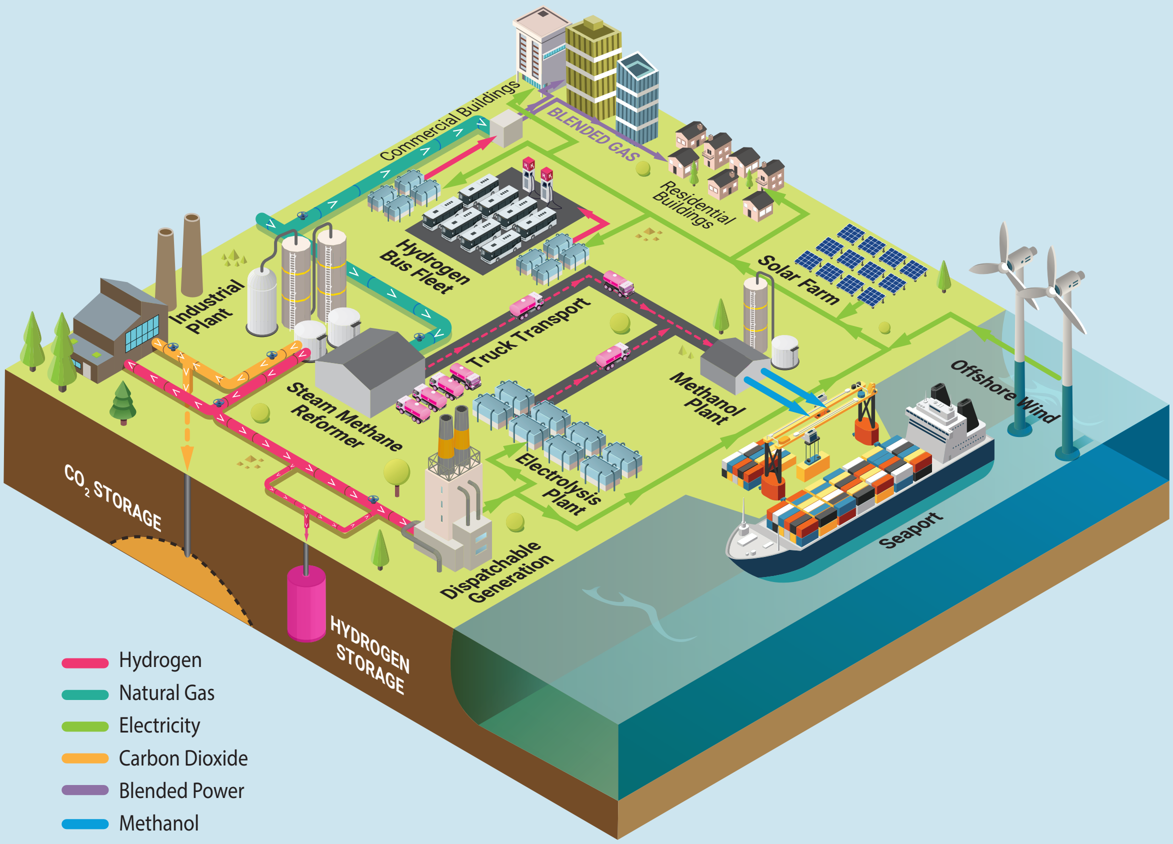
Box 1: Hydrogen as the backbone of low carbon regional hubs

The potential for hydrogen to play multiple roles in decarbonization across the economy—and the challenges often associated with transporting hydrogen long distances—present ripe opportunity for localized shared infrastructure and hydrogen hub development.

Regional opportunities for clean hydrogen can incorporate multiple methods of production, transport and storage, and end use. As shown in Figure 6, a hydrogen economy can include centralized production using a methane reformer, a dedicated pipeline, and shared CO_2 transport and storage infrastructure as well as decentralized production that generates hydrogen near the end use. Both centralized and decentralized production can benefit from broader market formation activity. For example, end-users of hydrogen that rely on truck transport can receive hydrogen from both large, centralized producers, and smaller decentralized producers. Multiple transport methods enable producers to follow market trends and seasonal variation, for example preferencing dispatchable generation in periods of low renewable output and preferencing mobility during peak seasons of travel.

Production facilities in a hydrogen hub can benefit by sharing infrastructure. Large customers, for example, can share dedicated pipelines that flow from a nearby production facility. Large hydrogen producers that use carbon capture can also share CO_2 transport and storage infrastructure with nearby emitters. For producers and consumers relying on truck-based transport, sharing roadways and decompression infrastructure can lower operating costs.

Figure 6: Hydrogen Economy Integration Across Multiple Sectors and Production Pathways



A regional hydrogen hub can provide pathways to decarbonize multiple sectors and use multiple production and transport pathways. In this example, hydrogen is produced by a SMR that uses carbon capture and several electrolysis facilities. Hydrogen is transported by both pipe and truck and used in the industrial, electric power, mobility, buildings, and shipping sectors. Electrolysis facilities use power from the bulk power supply as well as dedicated renewable resources.

U.S. Industry Activities in Clean Hydrogen Findings

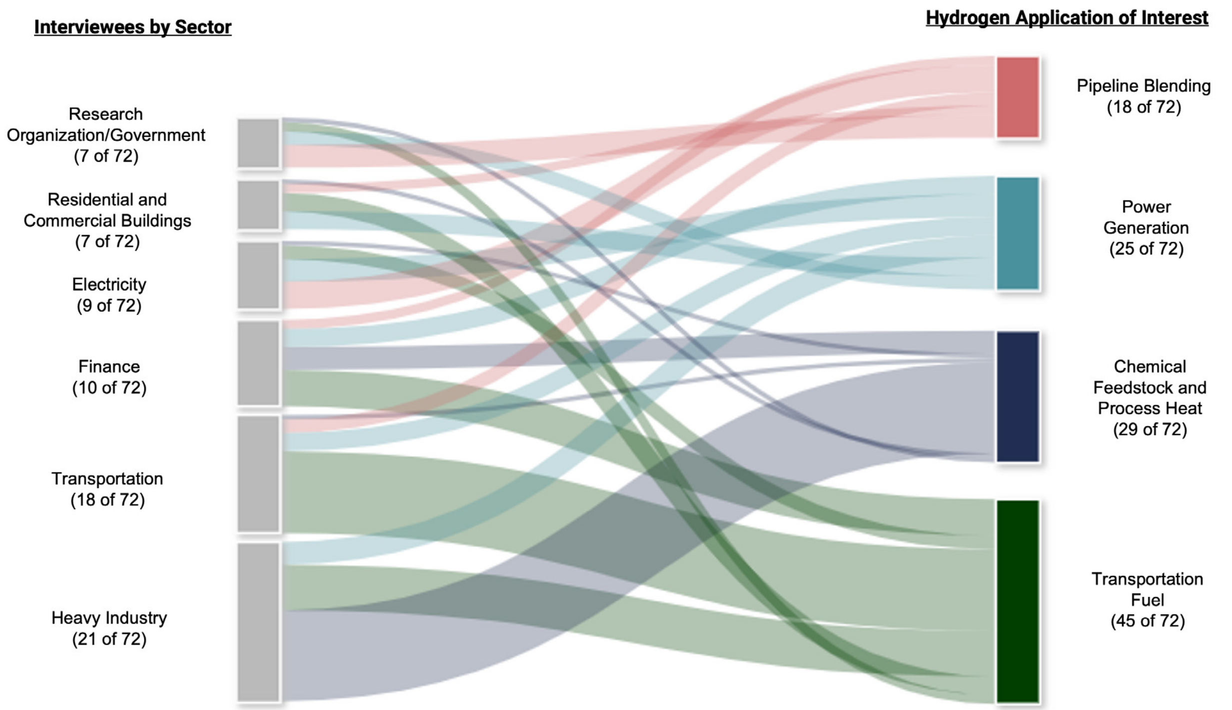
INDUSTRY INTERVIEW APPROACH

To understand industry activities in clean hydrogen and inform its analysis, EFI conducted 72 exploratory interviews with organizations from across the current and emerging hydrogen value chain that provide a snapshot of the rapidly evolving clean hydrogen investment environment. The interview approach, combined with the baseline context of the existing and emerging U.S. hydrogen markets, provides a synthesized view of the current business models being pursued by actors across the hydrogen value chain, the high-level logic behind their activities, and the relative maturity of hydrogen production and consumption pathways across a range of economic sectors and subsectors. A comprehensive description of the interview methodology is available in Appendix A.

The hydrogen value chain is comprised of the three primary phases of the hydrogen lifecycle: production, transport and storage, and end use. Adjacent sectors including regulation, finance, and research institutions are another key component of the value chain that could influence the future of the hydrogen economy.

Interviewees represented five general markets: transportation, heavy industry, finance, electricity, residential and commercial buildings, and research organizations and government entities. Figure 7 shows the current primary sector of the interviewed firms and the hydrogen applications in which they were actively engaged. Except for heavy industry and transportation, hydrogen demand for all applications is nearly nonexistent today, with different anticipated growth rates through 2050.[54]

Figure 7: Stakeholders Interviewed and Interest in Hydrogen Market



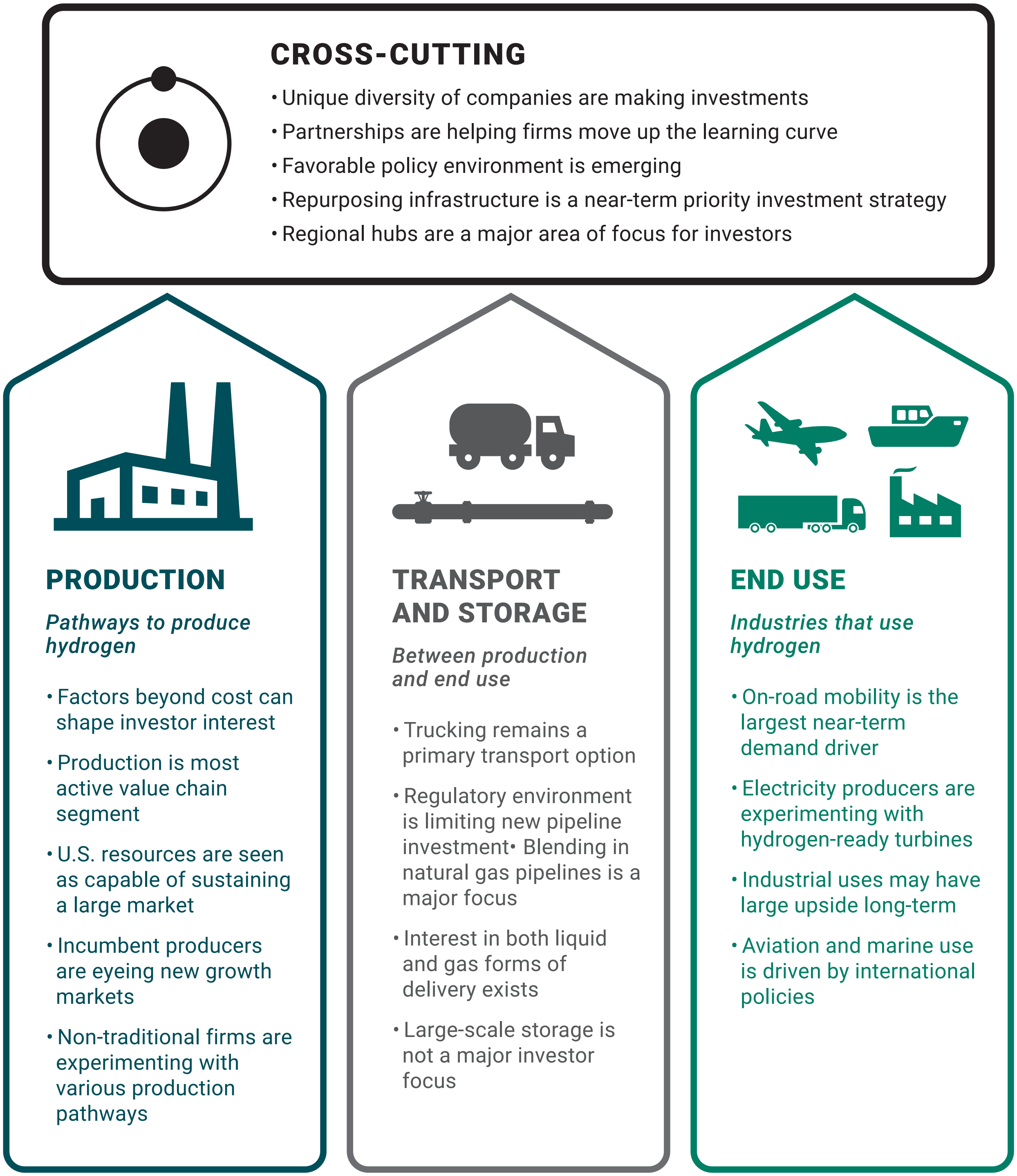
Across six sectors, 72 interviewees described interest in a variety of hydrogen end use cases. Those use cases fall under four applications: pipeline blending, power generation, chemical feedstock and process heat, and transportation fuel. Some interviewees expressed interest in more than one application, which led to multiple streams of interest from the same actor. Ultimately, more than half the interviewees expressed interest in transportation fuel. Approximately 60 percent showed interest in power generation, pipeline blending, or both. Another 40 percent are considering chemical feedstock and process heat applications.

The interviews addressed three high-level questions:

- How does each organization view the hydrogen market in the United States today and in the future?
- Where applicable, what is each company's specific value proposition and supporting business model in hydrogen?
- What does each organization see as the priority factors (enablers and deterrents) driving business decisions in clean hydrogen?

These interviews uncovered value chain-specific and cross-cutting findings (Figure 8). Value chain-specific findings comprise the key findings within production, transport and storage, and end use. These findings provide depth into the specific areas of interest within and, potentially, between value chain segments. The cross-cutting findings provide valuable perspectives on themes that were perceived to be common across most of the hydrogen activities in the United States. These findings can provide valuable framing around the questions: what is happening and why in the emerging clean hydrogen economy.

Figure 8: **Hydrogen Industry Findings: Views from Industry, Market Innovators, and Investors**



CROSS-CUTTING

- Unique diversity of companies are making investments
- Partnerships are helping firms move up the learning curve
- Favorable policy environment is emerging
- Repurposing infrastructure is a near-term priority investment strategy
- Regional hubs are a major area of focus for investors

PRODUCTION

Pathways to produce hydrogen

- Factors beyond cost can shape investor interest
- Production is most active value chain segment
- U.S. resources are seen as capable of sustaining a large market
- Incumbent producers are eyeing new growth markets
- Non-traditional firms are experimenting with various production pathways

TRANSPORT AND STORAGE

Between production and end use

- Trucking remains a primary transport option
- Regulatory environment is limiting new pipeline investment• Blending in natural gas pipelines is a major focus
- Interest in both liquid and gas forms of delivery exists
- Large-scale storage is not a major investor focus

END USE

Industries that use hydrogen

- On-road mobility is the largest near-term demand driver
- Electricity producers are experimenting with hydrogen-ready turbines
- Industrial uses may have large upside long-term
- Aviation and marine use is driven by international policies

This figure shows the major cross-cutting and value chain-specific findings that emerged from 72 exploratory interviews with organizations across the current and emerging hydrogen value chain, including production, transport and storage, and end use.

HYDROGEN PRODUCTION INDUSTRY FINDINGS

Summary: Many representatives of the organizations EFI interviewed were actively exploring options for clean hydrogen production pathways. Companies are exploring engineering options and business cases for myriad hydrogen production pathways ranging from century-old production via natural gas to concepts still in the research stage. **The diversity of production pathways under investigation shows that cost is one of several factors shaping company priorities.** Organizations emphasized **the flexible scalability of production technologies** when developing their strategies, noting that modest investments in production capacity—often those using electrolysis—help them gain experience with new technologies and reduce production costs, both of which will better position the company to compete on cost and convenience.

A foundational understanding that underpins industry activity is that **the United States is seen as having the necessary resources for growth of a large-scale hydrogen market**. Interviewees noted the country's natural resources, existing infrastructure, and technology acumen as reasons for optimism about the future for low-cost, low-carbon hydrogen. This optimism is shared by a wide range of companies: **incumbent hydrogen producers are looking to develop cleaner hydrogen products to capture new customers and non-traditional firms are experimenting with hydrogen production projects** to explore moving into new markets.

Table 4 shows the factors shaping the development of specific clean hydrogen production pathways including interested industries, market drivers, and market barriers. The sections that follow elaborate on these key interview findings.

Table 4: Factors Shaping the Development of Various Clean Hydrogen Production Pathways

	Natural Gas Reforming (SMR/ATR)	Coal Gasification	Natural Gas with Carbon Capture	Electrolysis Using Renewable Energy	Electrolysis Using Nuclear Energy	Electrolysis Using Grid Electricity	Methane Pyrolysis	Biomass & Waste Gasification
Market Readiness	Approximately 77% of national production comes from natural gas reforming	In previous decades, coal gasification was commonly used in the United States	Difficult to demonstrate because of large capital components to capture emissions	Many new projects operational or coming online in next few years, though capacities are small	Costly to co-locate nuclear and electrolysis facilities and safety implications are still unknown	The modular technology allows for low capital commitments; grid electricity is generally easy to access	Restricted to long-term, take-or-pay contracts for all produced commodities	Few upcoming projects which are generally small in scale, though RNG paired with SMR is currently ready and low cost
Estimated Costs ($/kg H2)[a]	$0.70-2.20	$1.00-2.50	$1.30-2.90[b]	$2.50-8.00	$5.00-5.40	$4.40-6.30	–	$6.80
Interested Industries	• Hydrogen suppliers and refineries already use and understand SMR/ATR technology	• No interest in coal gasification in the United States	• Those with existing assets (e.g., industrial gas companies), natural gas resources, and sequestration sites, and tax equity investors	• Utilities, pipeline operators, ammonia producers, and transit companies exploring decarbonization	• Utilities with existing nuclear assets interested in using or selling hydrogen	• Utilities want to install electrolyzers on-site to produce hydrogen for energy storage	• Venture capital and private equity investors because of multi-commodity production	• Tax equity investors because of the 45Q tax credit and producers interested in LCFS credit (through use of RNG)
Market Drivers	• The ATR process has lower temperature, energy, and coking requirements than traditional SMRs	None	• Opportunity to use existing assets • At-scale production already in development in the Gulf • 45Q offers additional revenue stream	• Modularity of electrolyzer units enables low-risk experimentation • Optimism that technology advances will drive down costs	• Hydrogen provides additional revenue for power plants in competitive energy markets	• National targets to decarbonize the grid will make electrolysis from grid less carbon intensive	• Produces a byproduct, carbon black, used in plastics, ink, rubbers, and other popular commodities	• Low carbon intensity using biomass or waste gasification with carbon capture • 45Q offers additional revenue stream
Market Barriers	• High capacity costs mean small and medium applications are not economical • Unabated and upstream emissions preclude applications for decarbonization	• Low natural gas and oil prices make this technology unattractive • Unabated and upstream emissions preclude applications for decarbonization	• Harder to experiment with than electrolyzers because it lacks modularity • Coordination across CO_2 capture, transport, and sequestration activities poses challenges	• High production cost and no mandate for low-carbon hydrogen • Smaller-scale electrolysis located closer to demand disadvantaged because of grid interconnection costs	• Difficult to secure vendors who have the skill and experience to build facilities in high security locations	• Current uncompetitive costs	• Carbon intensity benefits are lower than electrolysis with only renewables •Pyrolysis remains expensive compared to SMR/ATR technology	• Challenges with feedstock availability • Venture capital firms are skeptical of gasification business models

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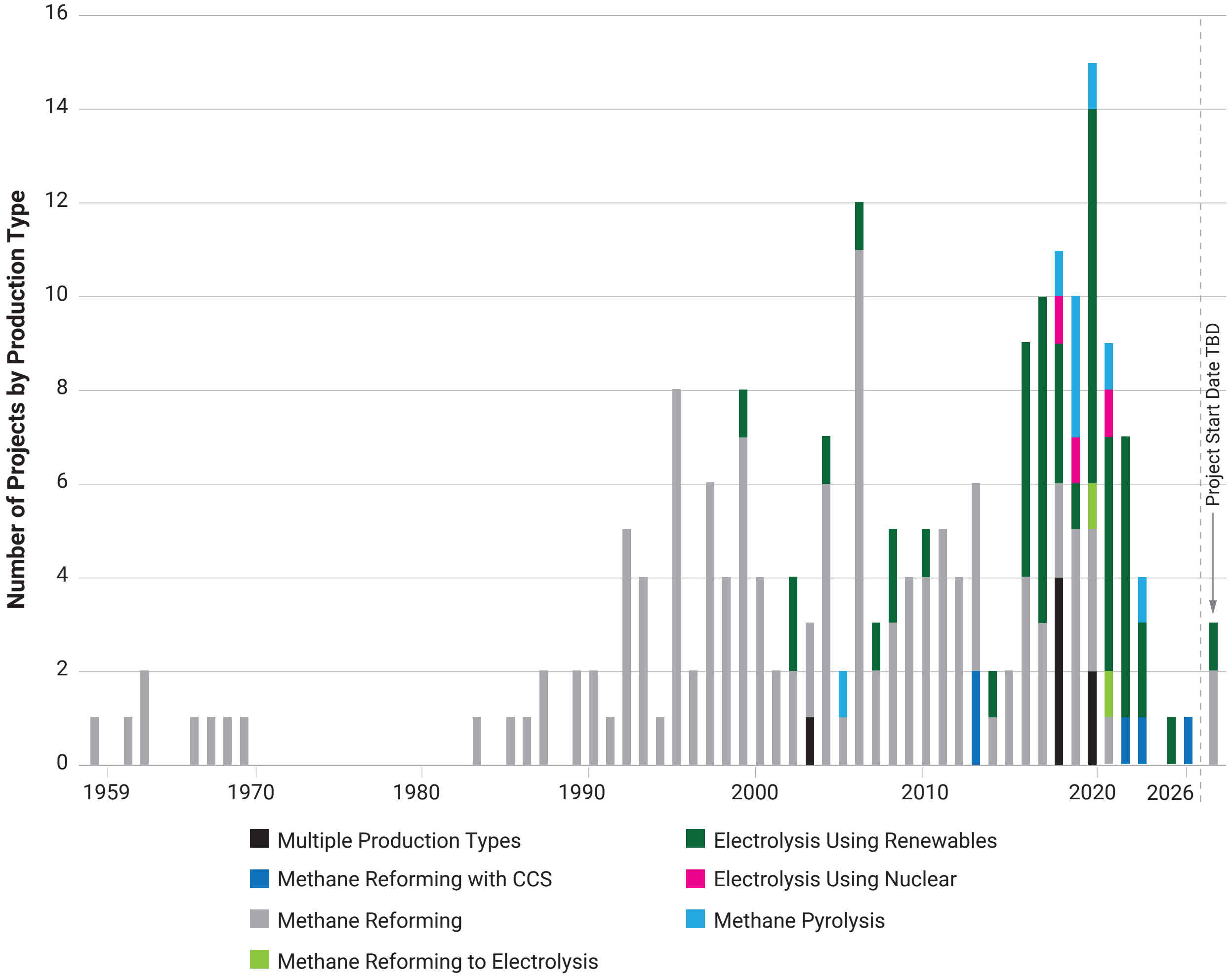
[a] See appendix for sources.

[b] Storage costs typically range from $2-5 per ton of CO_2 sequestered but can be as much as $10 per ton (Source: Labor Energy Partnership, “Building to Net-Zero: A U.S. Policy Blueprint for Gigaton-Scale CO_2 Transport and Storage Infrastructure,” June 2021.)

The diversity of production pathways under investigation shows that cost is only one of several factors shaping company priorities

Companies are exploring engineering and business cases for several hydrogen production pathways ranging from century-old production via natural gas to concepts still incubating in research labs (Figure 9). Companies raised the importance of several factors beyond cost influencing their clean hydrogen activities. Cost trajectories are hard to predict, they noted, particularly when incentive policies are under consideration in Congress; specific use cases, engineering, and human factors like safety and familiarity are more within a particular company's span of control. Simply put, each firm's current market position often shapes the hydrogen production pathway it explores.

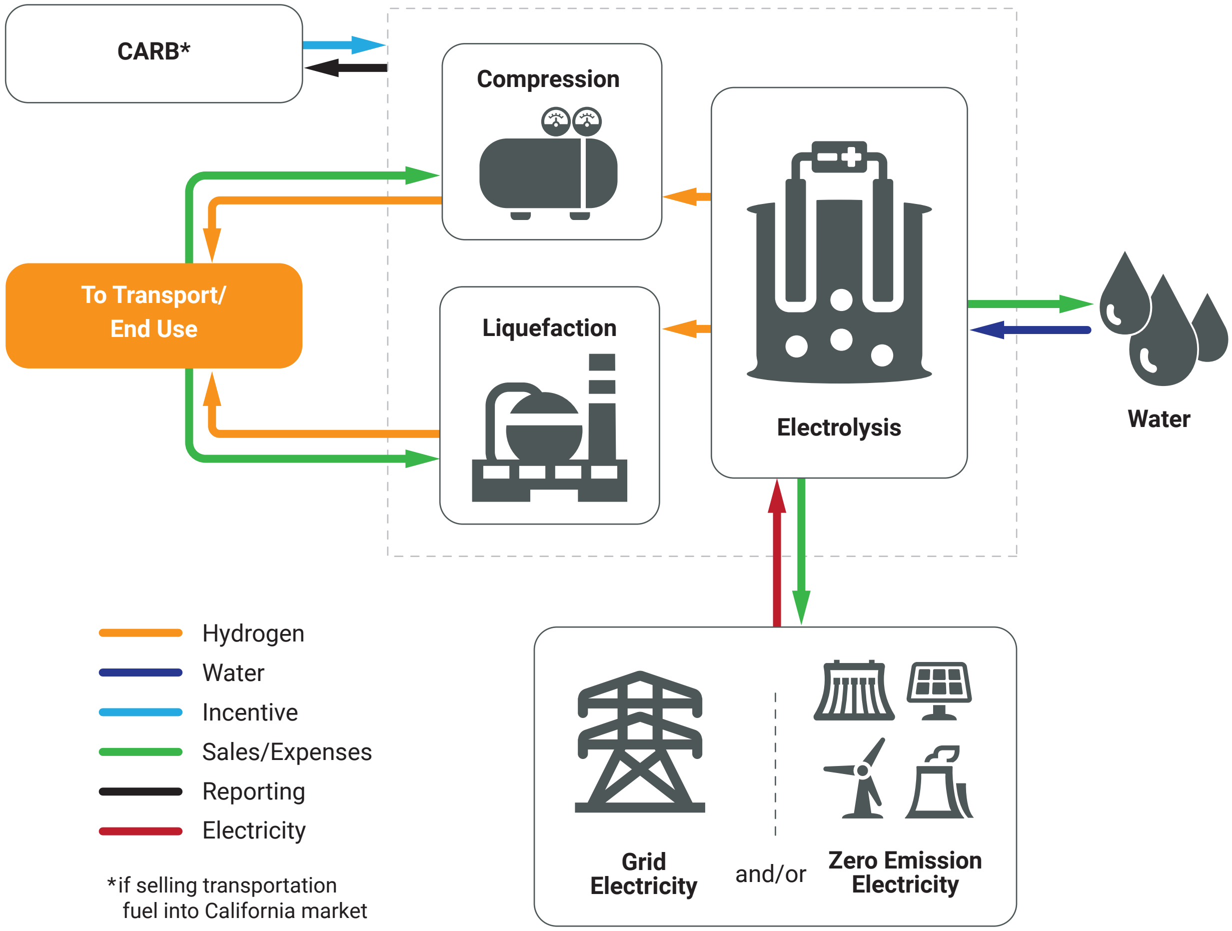
Figure 9: Number of U.S. Hydrogen Projects (Current and Planned) by Production Type from 1959 - 2026



The quantity of hydrogen projects, both operational and planned, has typically grown from 1959 through 2026 and the employed production methods have become more diverse. This figure includes 203 distinct publicly announced projects that use or produce hydrogen in the United States. Note: the right-most column tallies announced projects without a set start date.

The modularity of electrolysis has contributed to interest from a wide range of industries, including some that have not historically produced their own fuel. Electrolyzer units are offered in a range of sizes and require only water and electricity to operate. These features enable low-risk experimentation for companies curious about—but not yet committed to—hydrogen development. Figure 10 shows a conceptual business model for electrolysis-based hydrogen production.

Figure 10: Business Model of an Electrolysis Facility



The business model for hydrogen producers that use electrolysis relies on water supply, electricity, buyers, and the availability of incentives. The hydrogen producer can leverage incentives from the LCFS, operated by CARB, when selling into California markets for an additional revenue stream. The carbon intensity of these hydrogen producers depends on the use of zero emission electricity.

Larger-scale production pathways for clean hydrogen—including nuclear, natural gas with carbon capture, or natural gas pyrolysis—are also being pursued, though by fewer firms and typically supported by federal research and development funding. Companies noted that even though economies of scale may help lower production costs relative to electrolyzers, other factors like their high upfront capital requirements, the need for extensive supporting infrastructure (like CO_2 transport and storage infrastructure), and difficulty securing comparably sized counterparty agreements present barriers to immediate investment.

Hydrogen produced with natural gas and carbon capture faces these and other challenges. The rules governing compliance for a major source of revenue for these projects, the 45Q tax credit for carbon sequestration, creates uncertainty for what on paper appears to be a generous incentive.[55] Furthermore, new policy support that may be on the horizon, including the SCALE Act[c] and CATCH Act,[d] is also causing some prospective investors to pause decision-making.

Hydrogen safety is also an important factor shaping investment decisions. In general, the public—and in many cases the companies exploring hydrogen—are concerned with the safety risks of hydrogen. These concerns are focused on hydrogen's high flammability and explosivity.[56] One example of how safety is influencing market development is hydrogen producer interest in owning and operating equipment they use to produce hydrogen, even when their production facilities are located on a customer's property. Entering sales and service agreements allows the producer to operate and maintain their equipment to their own safety specifications and limit the risk of inexperienced third-party operation contributing to catastrophic accidents.

The flexible scalability of production technologies is making production an investment priority compared to other parts of the value chain

The portion of the clean hydrogen supply chain receiving the greatest focus by companies and investors is production. Investments in production are largely focused on gaining experience with new technologies and reducing production costs to better position the company to compete on cost and convenience for future sources of demand.

Hydrogen can be produced using various conversion processes, each using one of several feedstocks. In many cases, these processes produce valuable byproducts that contribute revenues; in other cases, hydrogen may be the byproduct. Companies exploring hydrogen also have unique assets, expertise, and business models and hope to capitalize on their unique market position. Policy support—like the LCFS or 45Q tax credit—benefit some pathways more than others. Given the nascency of some technologies and lack of thorough characterization of feedstocks and market opportunities, companies are also investigating emerging options with the potential for cost reductions or high market value on a speculative basis. The confluence and diversity of these circumstances around the country—namely the variety of production techniques and byproducts, companies' particular assets and expertise, policy-driven revenue opportunities, and unknown technology development trajectories—have led to the exploration of a number of distinct production pathways (Figure 11).

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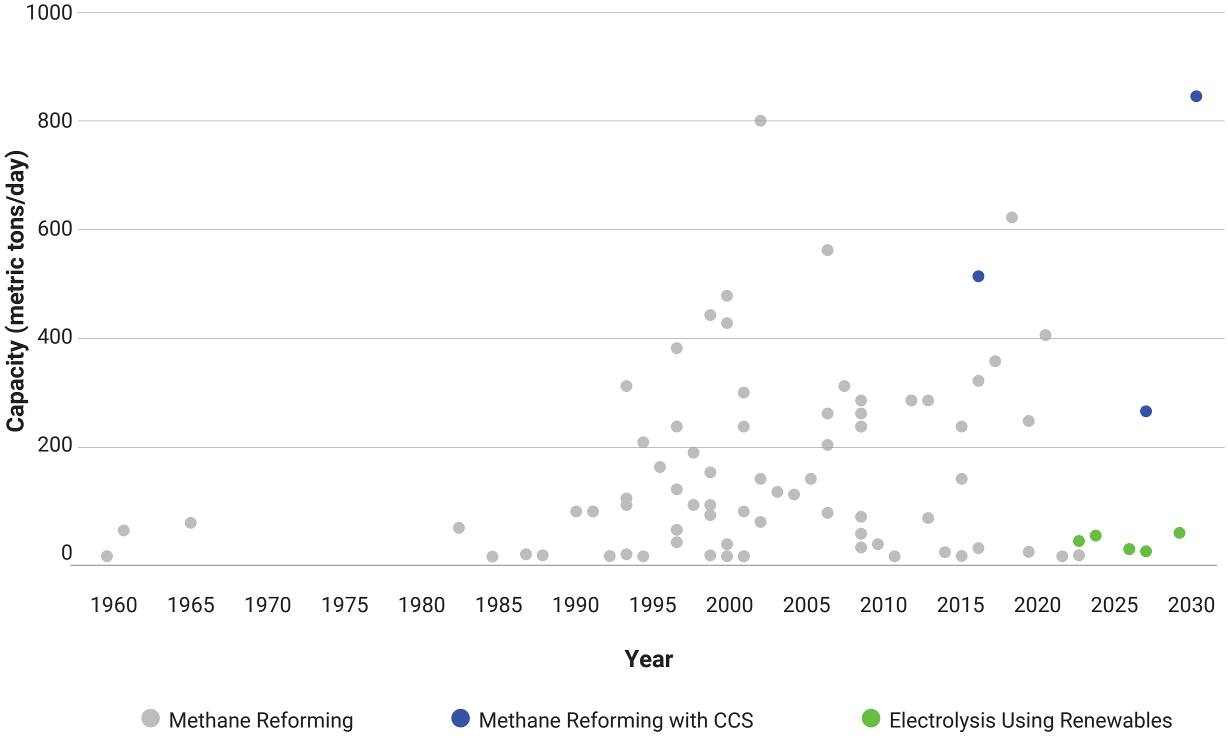
[c] The 2021 *Storing CO_2 and Lowering Emissions (SCALE) Act*, sponsored by Sen. Chris Coons (D-DE) in the Senate and Rep. Marc Veasey [D-TX] in the House would provide DOE cost sharing for commercial CO_2 storage hubs and establish programs to finance shared CO2 transport infrastructure.

[d] The 2021 *Coordinated Action to Capture Harmful (CATCH) Emissions Act*, proposed by Rep. Tim Ryan (D-OH), would increase tax credit levels for carbon capture from industrial facilities and power plants.

Many announced U.S. projects rely on electrolysis or biomass gasification hydrogen production pathways that are scalable, commercially available, and can be located near sources of existing demand (like refineries) or within a company's fence line, even if their levelized production costs are relatively high. Relative to other parts of the supply chain and larger production pathways like steam methane reforming with carbon capture, costs and the level of corporate commitment required to experiment with scalable production pathways can be low (Figure 11). Pipeline infrastructure and large-scale storage are expensive and face numerous financial and regulatory hurdles. Large sources of future demand like heavy-duty mobility are not yet commercially available. Other industrial sources of demand like steelmaking emit CO_2 and would require costly retooling of assets that may not be at the end of their useful lives. High-cost investments in high-demand end uses is only one of the challenges; reliability of the core business process, consistent access to adequate volumes of hydrogen, and re-training a workforce skilled in existing processes all present additional barriers to conversion. Scalable production pathways like electrolysis have the added benefit of enabling companies to simultaneously experiment with use cases, be it small gas turbines or a modest corporate vehicle fleet.

Figure 11: U.S. Hydrogen Project Production Capacity (Current and Planned) from 1960 - 2030



The capacity of hydrogen production projects, both operational and planned, has tended to grow between 1960 and 2030 and later projects have included low-carbon production methods. "Projects" are defined as publicly announced plants that produce hydrogen. Each plant is categorized based on its hydrogen production method. Given that not every current and planned hydrogen plant had public data on production capacity, this figure provides an estimate of relative capacities of the different production methods.

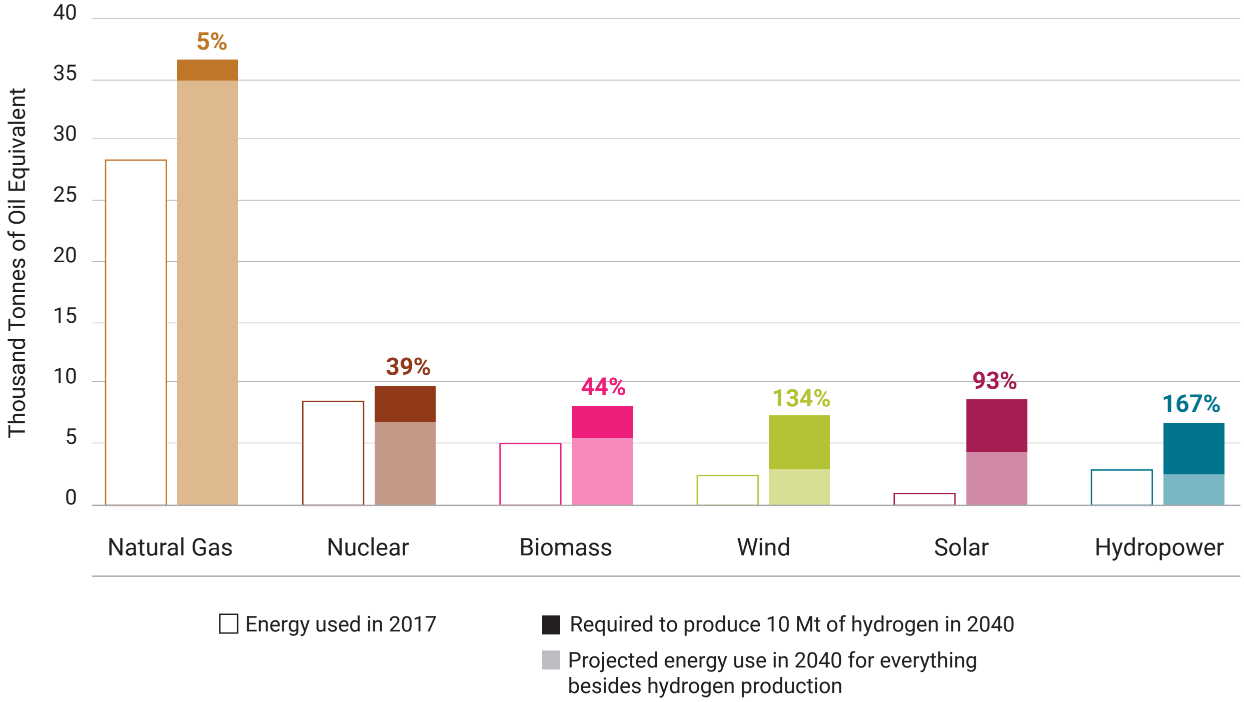
The United States is seen as having the necessary resources for growth of a large-scale hydrogen market

In interviews, investors expressed the belief that the United States is well-positioned to produce low-cost, low-carbon hydrogen. Interviewees reported that the country's natural resources, existing energy infrastructure, and history of technological innovation were significant drivers of investment for a range of hydrogen production pathways and technologies.

Organizations felt that the United States could meet feedstock, energy, and storage requirements for a range of hydrogen production pathways. They noted that renewable energy and other zero-carbon resources offer the low marginal cost and clean electricity generation needed for electrolysis, and natural gas provides feedstock for methane reforming and other production techniques.

Public sources also show that large regions of the country are well-suited to carbon dioxide storage and some locations are suited to salt caverns, which are ideal for hydrogen storage. For example, according to DOE H2@Scale program analysis, the United States has the domestic energy resources to meet projected hydrogen demand through 2040.[57] Figure 12 shows the energy use requirements by resource type to produce 10 Mt of hydrogen, compared to the total amount of that resource used in 2017 and project 2040 use.

Figure 12: Estimated Energy Requirements to Produce 10 Mt of Hydrogen, by Resource Type[58]



The energy input needed to produce 10 Mt of hydrogen could require significantly more renewable resources than are projected for 2040 in EIA's 2019 Annual Energy Outlook. Producing 10 Mt of hydrogen, for example, would only require consuming 5 percent more natural gas than projected to be used for all other uses in 2040. Producing 10 Mt of hydrogen from solar, however, would require over 90 percent more solar resources in 2040 than projected. Note: the percentages listed in the parentheses represent the percentage increase in 2040 projected energy consumption. Source: NREL, Data from EIA AEO 2019 Reference Case.

Existing infrastructure, including hydrogen production facilities, natural gas pipelines, and nuclear power plants, are viewed as opportunities for reducing costs and barriers to entry to large-scale hydrogen production and transport. Operational steam methane reformation facilities could be retrofit to lower carbon intensity. Existing pipelines that currently deliver natural gas feedstocks provide opportunities for pipeline blending and could be converted to carry pure hydrogen. Also, owners of existing nuclear power plants are investigating the use of their thermal and electric output for hydrogen production. Interviewees noted that expertise in energy production, markets, and business models that led to the United States' success in existing energy sectors could underpin the growth of U.S. hydrogen production, consumption, and markets.

Incumbent hydrogen producers are looking to develop cleaner hydrogen products to capture new customers

Coupling carbon capture with existing hydrogen production methods to create "blue" hydrogen is viewed by the interviewees as the leading decarbonization pathway for hydrogen incumbents. Interviewees stated that the maturity of technological carbon capture options and the existence of carbon capture development incentives, such as 45Q tax credits and state incentives like LCFS, support blue hydrogen production. The incumbents, however, expressed several concerns about this decarbonization pathway. First, policy uncertainty, notably that related to the 45Q tax credit, could disincentivize potential blue hydrogen developers. The SCALE Act,[e] introduced in the House and the Senate, and CATCH Act,[f] introduced in the House, could, however, provide additional financial and policy support for carbon capture infrastructure and

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[e] The 2021 *Storing CO_2 and Lowering Emissions (SCALE) Act*, sponsored by Sen. Chris Coons (D-DE) in the Senate and Rep. Marc Veasey [D-TX] in the House would provide DOE cost sharing for commercial CO_2 storage hubs and establish programs to finance shared CO2 transport infrastructure.

[f] The 2021 *Coordinated Action to Capture Harmful (CATCH) Emissions Act*, proposed by Rep. Tim Ryan (D-OH), would increase tax credit levels for carbon capture from industrial facilities and power plants.

storage if enacted. Second, some view carbon capture projects as limited by economies of scale; while the unit cost of hydrogen production coupled with carbon capture may be low (especially vis-à-vis production via electrolysis), project capital costs are high. Some also perceive carbon capture projects as currently lacking in standardization, increasing barriers to implementation and adoption. Finally, some expressed concern that policymakers do not perceive blue hydrogen to be a truly zero-carbon resource, and consequently that it may be disadvantaged in future policymaking.

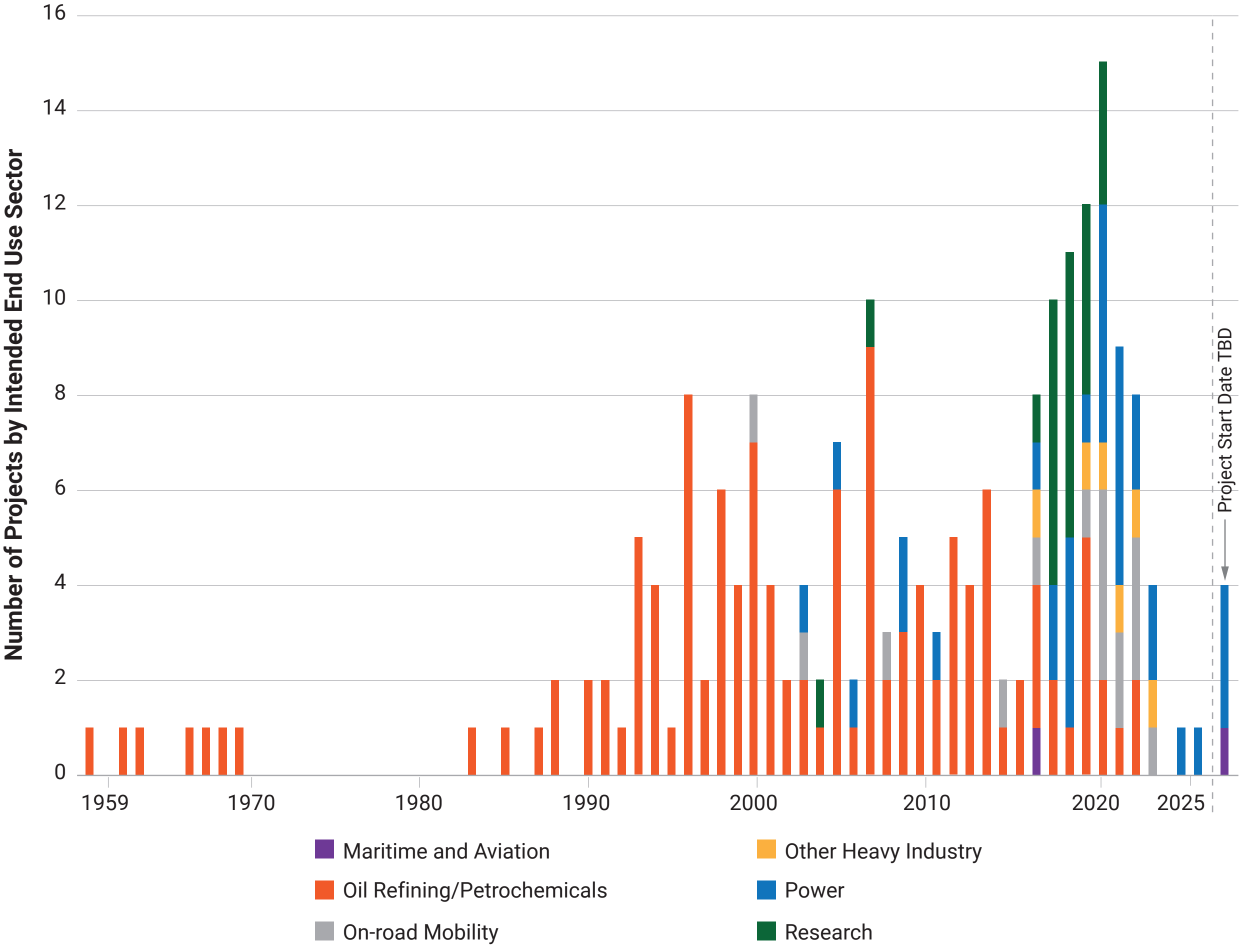
Another interest, according to multiple interviews, is reducing the carbon intensity of hydrogen production using renewable natural gas (RNG) as a feedstock for SMR plants. RNG is a “drop in” substitute for natural gas in existing SMR facilities, requires no pipe or other infrastructure retrofits to use onsite, and can make use of existing natural gas transmission pipeline infrastructure for wider distribution. RNG derived from certain feedstocks also has negative carbon intensity, meaning more carbon is prevented from entering the atmosphere over its lifecycle than is released into atmosphere when combusted. Fuels with negative carbon intensities are incentivized via policies like the California LCFS. Interviewees noted that multiple parties aim to secure RNG supply for hydrogen production; consequently, heavy competition for the commodity is anticipated over the next 5-10 years given its relatively small supply compared to natural gas and increasing demands for low-carbon fuels across the economy. Some interviewees expressed optimism that RNG supply will increase over time due to innovation in production methods and more efficient sourcing.

Non-traditional firms are experimenting with hydrogen production projects

New and non-traditional players are entering the hydrogen production market (Figure 13). Many of these new players described how and why they are experimenting with hydrogen production technologies. For example, utilities, especially those with existing natural gas assets like distribution pipelines and combustion turbines, noted their involvement in the early stages of pilot projects to blend hydrogen with natural gas. Some utilities are interested in hydrogen as a transportation fuel. Multiple utilities said that electrolyzers are the preferred hydrogen production technology due to their modularity, zero direct emissions, and relatively low capital costs compared to SMR with carbon capture. Gas transmission companies, on the other hand, were considering entering the market as hydrogen producers (via electrolysis and SMR with carbon capture) and transporters of hydrogen from areas with significant potential for renewable electricity-powered electrolysis to demand centers via existing or new pipeline infrastructure.

Some potential end-users of hydrogen, like truck fleet operators, are building their own electrolysis or SMR facilities, primarily to diversify energy supplies and mitigate operational risks. These self-suppliers often anticipate opportunities to sell to other entities in the future. However, interviewees noted that additional distribution, transmission, storage, and other associated infrastructure may be required near the production site to significantly scale up production loads and move hydrogen to potential customers.

Figure 13: Number of Hydrogen Projects by Intended End Use Sector in the United States



The quantity of hydrogen projects, both operational and planned, has generally grown from 1959 through 2026 and the composition of projects by their intended end use sector has become more diverse. This figure includes 203 distinct publicly announced projects that use or produce hydrogen in the United States. Research projects that specify the intended end use of the research were placed in the corresponding category; otherwise, research projects were categorized as "Research." Note: the right-most column tallies announced projects without a set start date.

New players in the market are also pursuing hydrogen production alternatives to electrolysis or methane reformation. For example, gasification and pyrolysis of biogenic feedstocks from forestry, agriculture, and ranching operations, as well as municipal solid waste diverted from landfill, can produce low-to-negative carbon hydrogen. While sensitive to the location and quantity of available feedstocks, these innovative production pathways are attracting attention, including from venture capital and private equity firms.

HYDROGEN TRANSPORT AND STORAGE INDUSTRY FINDINGS

Summary: Companies active in hydrogen transport and storage are strengthening their established transport and storage capabilities used to meet the nation's existing hydrogen demand and exploring new options for integrating hydrogen into existing infrastructure.

Pipelines are the most cost-effective way to transport large volumes of hydrogen, though many companies reported that the **uncertain regulatory environment is deterring hydrogen pipeline investment in the near-term**, especially since the location and scale of future hydrogen demand is so uncertain. For this reason and others, **blending hydrogen into natural gas pipelines is the most active area of investigation in the transport and storage value chain segment**. Existing natural gas pipelines and the end users they serve are believed to be able to accommodate modest proportions of hydrogen without requiring major upgrades or comprising safety. Blending hydrogen into natural gas pipelines provides an immediate use for clean hydrogen and can lower the carbon content of thousands of appliances and other end uses; it has therefore captured the attention of the private and public sectors alike.

Both incumbents and new entrants **see trucking as a near-term hydrogen transport option to meet growing market demand**. New sources of hydrogen demand are typically small and isolated relative to the large industrial facilities that consume most hydrogen today, ideally suited to trucked shipments from existing and new sources of production.

There was little focus of the interviewees on hydrogen storage options. There is company **activity in both gaseous and liquid storage options**, often to serve the same end use sector. Over time, companies anticipate one of these storage options to predominate as the market matures. **Large-scale hydrogen storage is not seen as a near-term priority growth area** for industry participants, though there exists a limited number of large-scale storage facilities in the Gulf Coast and one in development in Utah.

Table 5 shows the factors shaping the development of specific clean hydrogen transport and storage pathways including interested industries, market drivers and market barriers. The sections that follow elaborate on these key interview findings.

Table 5: Factors Shaping the Development of Hydrogen Transport

	Transporting Hydrogen					Hydrogen Carriers	
	Truck (Liquid)	**Truck (Gas)**	**Pipeline**	**Maritime**	**Rail**	**Ammonia**	**Methanol**
Market Readiness	• Common delivery method for small liquid hydrogen market • U.S. producers together possess about 140 liquid hydrogen trailers[59]	• Delivery method with use for warehouses employing material handling, stationary fuel cells, and tanks	• Only 1,600 miles of dedicated hydrogen pipelines limited to ports, major freight corridors, and oil refineries [60]	• Maritime transport of hydrogen not commercially available today	• Rail transport of hydrogen not commercially available today	• Over 3,000 miles of U.S. ammonia pipelines[61] • Centralized production is connected to demand centers via truck and rail	• About 10 million metric tons of U.S. annual methanol production [62] • Largely exported or confined to U.S. ports
Approximate Cost	**Medium/High.** • Better cost efficiency than delivering hydrogen gas • Requires capital investment in cryptogenic tanks and equipment	**Medium.** • Less capital intensity compared to pipelines • Lower capital expense compared to liquid trailers	**Low.** • Less capital intensity compared to pipelines • Retrofitting natural gas pipelines can reduce costs compared to building new dedicated hydrogen pipelines	**Medium/High.** •High capital expenses for containers •Greater carrying capacity per delivery than on-road trailers	**Medium/High.** • High capital expenses for rail tank cars • Greater carrying capacity per delivery than on-road trailers	**Medium.** •Existing ammonia transport is cost effective • Conversion to hydrogen is expensive with little current infrastructure	**Medium.** • Existing methanol transport is cost effective • Conversion to hydrogen is expensive with little current infrastructure
Interested Industries	• LNG operators • Industrial gas companies (existing capacity) • Aviation/Maritime ports • HDV (haulage and drayage) • Refineries • Midstream transport operators	• Industrial gas companies (existing capacity) • Aviation/Maritime ports • HDV (haulage and drayage) • Refineries • Midstream transport operators	• Gulf Coast ports, major freight corridors • U.S. utilities • Gas companies	• Maritime transport companies	• Uncertain	• Ammonia producers	• Maritime transport companies • Shipping Industry
Market Drivers	• Low regulatory complexity • Carries twice the mass of a gaseous trailer • Few technical barriers • Avoids pipeline permitting and construction • More appropriate for urban applications	• Low regulatory complexity • Few technical barriers • Avoids pipeline permitting and construction • Lower capital expenditures than liquified trailers	• Hydrogen pipelines exist near ports and freight corridors • Blending with natural gas is less costly compared to repurposing pipelines, though hydrogen volume is limited	• Larger capacity compared to road trailers • Can increase the mobility of and access to hydrogen	• Larger capacity compared to road trailers	• Robust international market • Existing transport infrastructure • Can reduce transport challenges compared to pure hydrogen	• Can reduce transport challenges compared to pure hydrogen • Existing infrastructure in U.S. port system • Currently produced in large quantities
Market Barriers	• Less energy efficient than gaseous transport due to cryogenic conditions. • Higher capital costs than gaseous trucking • More safety concerns than gaseous hydrogen • Requires a centralized value chain due to higher capital costs	• Significant operating expenses compared to pipeline transport • Only able to carry about half the mass of hydrogen in a gaseous trailer compared to a liquid trailer	• Gas infrastructure suitability limits blending • Repurposing pipelines lacks regulatory clarity • Hydrogen blends can increase NO_x emissions when combusted	• High capital expenditures • Jones Act would make domestic shipping of hydrogen difficult	• High capital expenditures	• High toxicity limits applications near large populations • Considered too dangerous to use in enclosed spaces (e.g., ships, airplanes). • Converting ammonia to hydrogen is costly and inefficient	• Methanol projects difficult to de-risk because it lacks the same hedging or derivative market as natural gas • Still produces CO_2 emissions • Applications limited to shipping transport and the U.S. port system

Trucking is seen as near-term hydrogen transport option as the market grows

New sources of hydrogen demand are typically small and isolated relative to the large industrial facilities that consume most hydrogen today. This new demand is being met primarily in two ways: new small-scale local production facilities, and trucks delivering hydrogen from existing large-scale facilities. Interviews suggest that incremental new demand will continue to be met using these two approaches in the near-term. Hydrogen pipelines and other modes of transport like rail and maritime are anticipated to be cost effective at much later stages of market development.

Shipping hydrogen via trucks is costlier than pipeline transport on a unit basis. However, companies emphasized the flexibility, adaptability, and scalability of truck-based shipping relative to fixed-route modes. Existing hydrogen pipelines are short and may not be located near sources of new demand, and new pipelines were thought to be too costly and too regulated to pursue at this stage of market formation. In California, for example, more than 100 additional hydrogen fueling stations are planned to be built across the state by 2025. Established industrial gas companies are expected to supply these new facilities by truck from new and existing large facilities both in and out of state.

Uncertain regulatory and market environments are deterring hydrogen pipeline investment

The lack of a robust hydrogen market is a major factor affecting investor thinking regarding the need for new pipelines. However, speculation over market growth does animate interest in the need for low-cost transport options. Other significant near-term barriers to pipeline investments were reported by the interviewees. The lack of clearly defined regulations and regulatory jurisdictions appear to be important factors in choosing the types of near-term projects. Pipeline infrastructure that is often difficult to plan, permit, and site was highlighted as a major contributor to a particularly uncertain regulatory environment.

According to public sources, the Pipeline and Hazardous Materials Safety Administration (PHMSA) is the office in the Department of Transportation (DOT) charged with regulating cross-state hazardous material transport. Companies mentioned PHMSA's pipeline regulations, largely tailored to natural gas systems, are poorly adapted to the unique characteristics of hydrogen. Seeming minutiae like welding techniques, steel requirements, and leak detection rules need to be updated to reflect hydrogen's unique characteristics.

Some interviewees pointed to the Natural Gas Act (NGA) as providing the most relevant guidance for congressionally delegated regulatory authority for interstate hydrogen trade. Under the NGA, the Federal Energy Regulatory Commission (FERC) has the primary authority for interstate pipeline regulation, including eminent domain and tariff regulation. Whether hydrogen would fall under the delegated NGA authorities and permissible blend rates is unclear in both the authorizing language and associated regulations, creating enormous regulatory uncertainty for potential hydrogen pipeline investors.

Some companies are looking to hydrogen carriers and hydrogen-based alternative fuels to avoid regulatory issues for hydrogen pipelines. Some alternative fuels are discussed in Box 2.

Box 2: Hydrogen-Based Alternative Fuels

In addition to direct use of hydrogen, alternative fuels that are produced with hydrogen—such as ammonia, methanol, and methane—can become another component of the future hydrogen economy. Ammonia, methanol, and methane all have established markets, infrastructure, and production methods, making these chemicals attractive decarbonization vectors. Hydrogen-based alternative fuels can either be used directly (e.g., ammonia-fueled ships) or as hydrogen carriers, where the chemical is converted back to hydrogen near the point of use.

Ammonia

Ammonia has robust existing infrastructure including 3,000 miles of pipelines and a large international market. Using ammonia as a fuel is often discussed as a method to decarbonize the maritime industry; however, concerns about ammonia's toxicity have limited its adoption. Exposure to ammonia can cause burning of the eyes and throat, lung damage, and even death. Maritime companies and airlines were especially concerned about the prospect of workers and customers being near ammonia tanks and pipes on vessels and at ports, should a catastrophic leak occur. While ammonia is carbon-free, combustion of ammonia produces nitrous-oxides (NO_x) which are harmful pollutants for local air quality.[63]

Methanol

The United States produces about 10 million tons of methanol annually, which is mostly exported to China. The maritime industry indicated interest in methanol fuel, in part because it is already available at many major global ports.[64] Additionally, methanol carries more hydrogen per cubic meter than liquid hydrogen, making methanol an effective medium to store and transport hydrogen.[65] However, while methanol does produce significantly less NO_x, sulfur-oxides (SO_x), and particulate matter emissions compared to diesel engines, combusting methanol produces CO_2 and fully decarbonizing relies on using captured CO_2 to produce methanol.

Methanation

Converting CO_2 and hydrogen into methane, the methanation process, can allow natural gas infrastructure to be used in a decarbonized economy. Maintaining existing infrastructure could significantly lower costs and promote broader adoption of low-carbon fuels. While gas infrastructure can only accommodate up to 20 percent hydrogen, methane produced with clean hydrogen can replace fossil gas up to 100 percent. However, the methanation process involves energy losses and costs significantly more than natural gas, but innovation and supportive policies could lower these barriers.[66]

Blending hydrogen in natural gas pipelines is the most active area of investigation in the transport and storage value chain segment

Building new, dedicated pipelines for transporting hydrogen requires large investments and relative certainty in the future location and scale of hydrogen value chains—something that remains elusive in the near-term clean hydrogen market. Blending hydrogen into natural gas pipelines, however, provides an immediate use for clean hydrogen and can lower the carbon content of thousands of appliances and other end uses, since burning hydrogen provides energy without releasing CO_2. Substituting 20 percent of the current natural gas supply by volume with hydrogen could create a demand of 44,000 tons per day, or 16 Mt per year, in 2050.[67] This potential dual benefit—aiding in market formation and multi-sectoral carbon reductions—has captured the attention of both the private and public sectors.

Multiple interviewees agreed that existing natural gas infrastructure can accommodate hydrogen blends up to 20 percent, which is aligned with rates described in public studies.[68,69] However, the interviews made clear actual blend rates will be determined on a case-by-case basis. Adding hydrogen to a natural gas system can affect pipeline material, equipment, and operations; in particular, research has shown that hydrogen can cause pipeline embrittlement, which can lead to catastrophic failure and requires more frequent repairs, maintenance, and monitoring of pipelines. These issues are being actively researched by individual companies, industry organizations, and research institutions. Additionally, not all consumers can use a blend of natural gas and hydrogen as high as what a pipeline may be able to carry. As detailed in Box 3, further research and testing is ongoing to identify regional blending applications.

Box 3: Hydrogen Blending Projects in the United States and Around the World

In late 2020, two California utility companies—Southern California Gas Company (SoCalGas) and San Diego Gas and Electric Company (SDG&E)—announced the nation's first demonstration project to blend hydrogen into natural gas supply.[70] The project would start by blending 1 percent of hydrogen in an isolated section of SoCalGas's distribution system. The blending could then be scaled up to 20 percent (by volume). The project's aspiration is to produce hydrogen from electrolysis using excess renewable energy; however, initial hydrogen supply would be trucked in from a third party to expedite testing.[71]

Another major utility, National Grid, also announced a hydrogen blending study in 2020. National Grid will assist research on blending hydrogen in natural gas pipelines, in partnership with six national laboratories and 20 industry and academic institutions.[72] Funded through DOE's H2@Scale program, the research will focus on hydrogen pipeline compatibility, costs, environmental impact, and the effect on appliances and other equipment in buildings.[73]

Across the world, there are at least 13 projects spanning three continents that are testing hydrogen blends for a variety of customers and end uses.[74] Of these projects, five are currently operational,[g] seven exclusively serve residential customers, two exclusively serve industrial customers, and three serve a mix of residential, commercial, and industrial customers. The blend rate of hydrogen ranges from 2 to 20 percent for residential uses; blend rates for industrial uses range from 10 to 100 percent.

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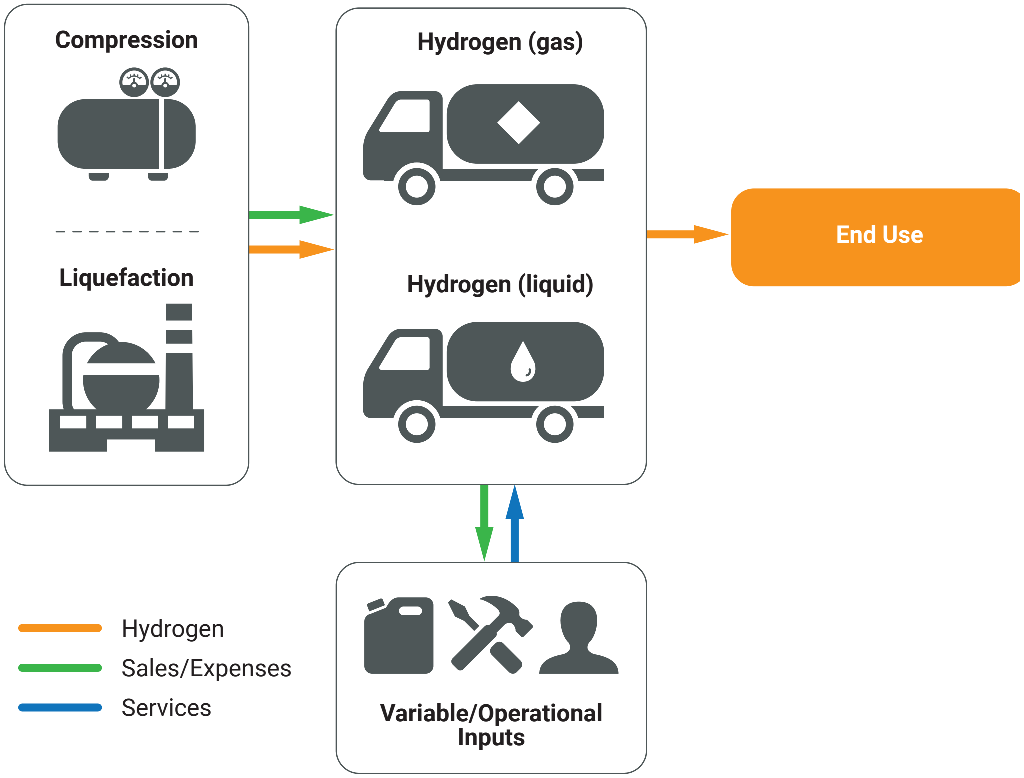
[g] Four projects are listed as operational in the cited material; however, one additional project became operational (AGN, Australia, Adelaide suburbs) since the time of publication.

Liquid and gaseous delivery are both viable transport options in the near-term

Liquid and gaseous transport methods are both receiving attention from investors. The near-term flexibility, adaptability, and scalability of trucking has made it the dominant mode of hydrogen transport, for both liquid and gaseous hydrogen (Figure 14). The debate between liquid and gaseous hydrogen was particularly prevalent with interviewees in the light-duty vehicle (LDV) market as they decide which phase is preferable for delivery to LDV fueling stations. Although fuel cell vehicles operate on gaseous hydrogen, fueling stations can store liquid hydrogen on-site and convert to gaseous hydrogen before fueling or simply store gaseous hydrogen.

Figure 14 : Business Model of an On-Road Truck Delivery System



The business model for on-road transport of hydrogen as both a liquid and a gas. This business model does not depend on production type, but hydrogen can either be delivered in gaseous or liquefied form. Variable and operational inputs (such as maintenance and operations) facilitate the transport of hydrogen to its end use.

Transporting liquid hydrogen by truck delivers more hydrogen per delivery than gaseous transport and allows for a smaller storage footprint for a fixed amount of hydrogen. Investors noted that these qualities make liquid hydrogen transport particularly attractive because it reduces the required storage footprint at fueling stations and the frequency of deliveries. However, there are higher capital expenditures for the liquid hydrogen because liquefaction—which consumes nearly 35 percent of hydrogen's energy content—is less energy efficient than gaseous delivery and requires more specialized equipment. Investments in specialized tube trailers are also necessary to maintain low temperatures during transport. Fueling station owners receiving liquid hydrogen also have capital expenses for the equipment needed to store the liquid hydrogen and convert it to a gas for on-site fueling.

In addition to cost, safety is a primary concern for investors regarding the transport of both liquid and gaseous hydrogen, particularly for onsite storage at fueling stations where hydrogen and the general public are in close proximity. The high volume at a low pressure of liquid hydrogen slows the dissipation of hydrogen in the event of a leak. This slow dissipation could increase the risk of a fire because of hydrogen's low ignition limit. Gaseous hydrogen, in contrast, is stored at much higher pressure so dissipation is more rapid, but an explosive event is relatively more likely.

It was implied by the interviewees that the adoption of either liquid or gaseous hydrogen transport will likely depend on space constraints and local ordinances regarding truck delivery frequency. These conditions may ultimately dictate delivery feasibility, necessary equipment, and the fuel that guarantees supply at the lowest lifecycle cost. For example, a more geographically distributed value chain may opt for liquid transport to reduce delivery frequency, while a more centralized value chain may choose gaseous transport to avoid higher capital expenditures. This market division between liquid and gaseous hydrogen transport will also depend on site-specific safety concerns. Safety ordinances at the local level and the hydrogen's proximity to other flammable or reactive fuels will likely dictate the type and placement of on-site storage, which subsequently influences the demand of either form of hydrogen transport.

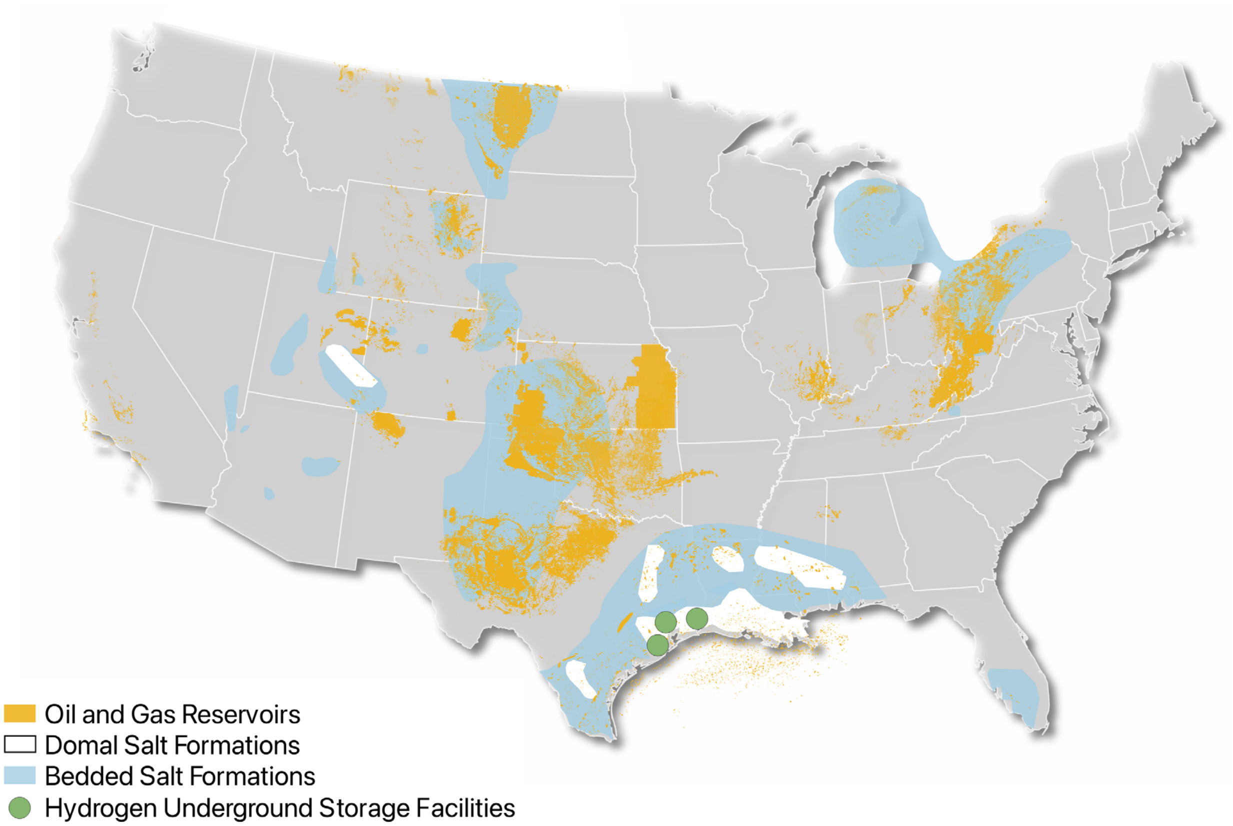
Large-scale hydrogen storage is not seen as a near-term priority growth area

Large-scale storage in underground caverns or reservoirs did not elicit near-term company interest along the value chain. The fact that it was not mentioned by interviewees as a priority area may be informative to the direction of the emerging hydrogen market. Large upfront costs, the ability to produce hydrogen close to where it is needed, and a long history of storing hydrogen safely above ground are seen as headwinds to large-scale hydrogen storage development.

According to public sources, most hydrogen is currently stored in tanks close to where the hydrogen is consumed, and companies expressed little interest in deviating from this status quo in the near-term.[75,76] In California, for instance, fueling stations for LDVs and heavy-duty vehicles (HDVs) are equipped with tanks that can hold liquid and low- or high-pressure gas.[77] Across all identified existing and potential end users in Table 6, near-term projects are generally small in scale and do not require large-scale hydrogen storage components.

To provide context, the United States has some of the largest geologic storage resources in the world (Figure 15). In Louisiana, the Bayou Choctaw site holds approximately 76 million barrels of oil reserves in large underground caverns carved out of salt.[78] That same cavern could hold up to 0.44 Mt of gaseous hydrogen stored at 700 bar, or the equivalent of four percent of annual U.S. hydrogen demand.[79] At nearby sites in Texas, albeit on a smaller scale, three underground salt caverns are used to store hydrogen. The largest of the three, Spindletop, has a capacity of just 0.0036 Mt of hydrogen.[80]

Figure 15 : Potential Underground Formations for Hydrogen Storage[81,82]



The continental United States has areas where underground geologic formations may make large-scale hydrogen storage feasible. Storage in oil and gas reservoirs and in salt caverns in domal salt formations were identified as potential areas of further exploration in interviews. Data from the National Energy Technology Laboratory and Earth Resource Associates.

Additionally, federally funded projects tend to prioritize fuel cell research over underground storage. One exception to this general market trend is the Advanced Clean Energy Storage (ACES) project, which is set to store approximately 150,000 MWh of energy in an underground salt cavern. The cavern will store hydrogen and compressed air and is expected to be operational by 2025.[83]

However, like CO_2 sequestration, underground storage will be region specific and could require extensive geologic assessments to ensure proper siting, which could be expensive and time consuming. Additionally, areas suitable for salt caverns are primarily located off the Texas and Louisiana Gulf. Bedded salts—a distinct geologic feature from the domal formations hosting the Gulf's large-scale storage caverns—are distributed in several regions across the country; they are not, however, being considered for storage applications in the near-term because they are shallow and would therefore require many more caverns to be drilled, leading to higher costs and more brine disposal.[84]

HYDROGEN END USE INDUSTRY FINDINGS

Summary: Most interviewees see **on-road mobility as the largest near-term growth area for clean hydrogen demand**. Companies entering the clean hydrogen production market regularly cited the mobility sector as the business rationale for scaling up, noting there are more policies supporting hydrogen's use in the mobility sector than for any other application. Light-duty vehicles and forklifts are already commercially available, and several companies are developing heavy-duty vehicles that should be commercial in the near-term.

For pre-commercial end uses outside of the mobility sector, company activities range from early exploration to active demonstration projects. **Electricity producers are experimenting with hydrogen-ready turbines and hydrogen production opportunities**. Early mover activity often involves the use of electricity to produce hydrogen, hydrogen to produce electricity, or reusing electricity-producing assets for hydrogen production. Often these activities are led by the electricity industry itself, guided by compelling business rationales.

There is investor interest in employing hydrogen as a decarbonization pathway in the industrial sector, despite not being seen as a first mover. Industrial end-users such as cement, steel, and glass broadly agreed that hydrogen is a potential pathway to decarbonize their respective sectors but highlighted the challenge of managing higher costs while participating in competitive global markets. The prospect and uncertain costs and development timeline of alternative clean energy options—including electrifying end uses and carbon capture—were also noted. Lastly, **aviation and maritime end uses are under exploration, primarily driven by stringent international and European emissions reduction targets and consumer pressure**. Although these end uses have long engineering and development timelines, manufacturers and operators of planes and ships are eager to create clean energy options in the face of pending international emissions standards.

Table 6 shows the factors shaping the development of specific clean hydrogen end use pathways including interested industries, market drivers, and market barriers. The sections that follow elaborate on these key interview findings.

Table 6: Factors Shaping the Development of Hydrogen End Uses

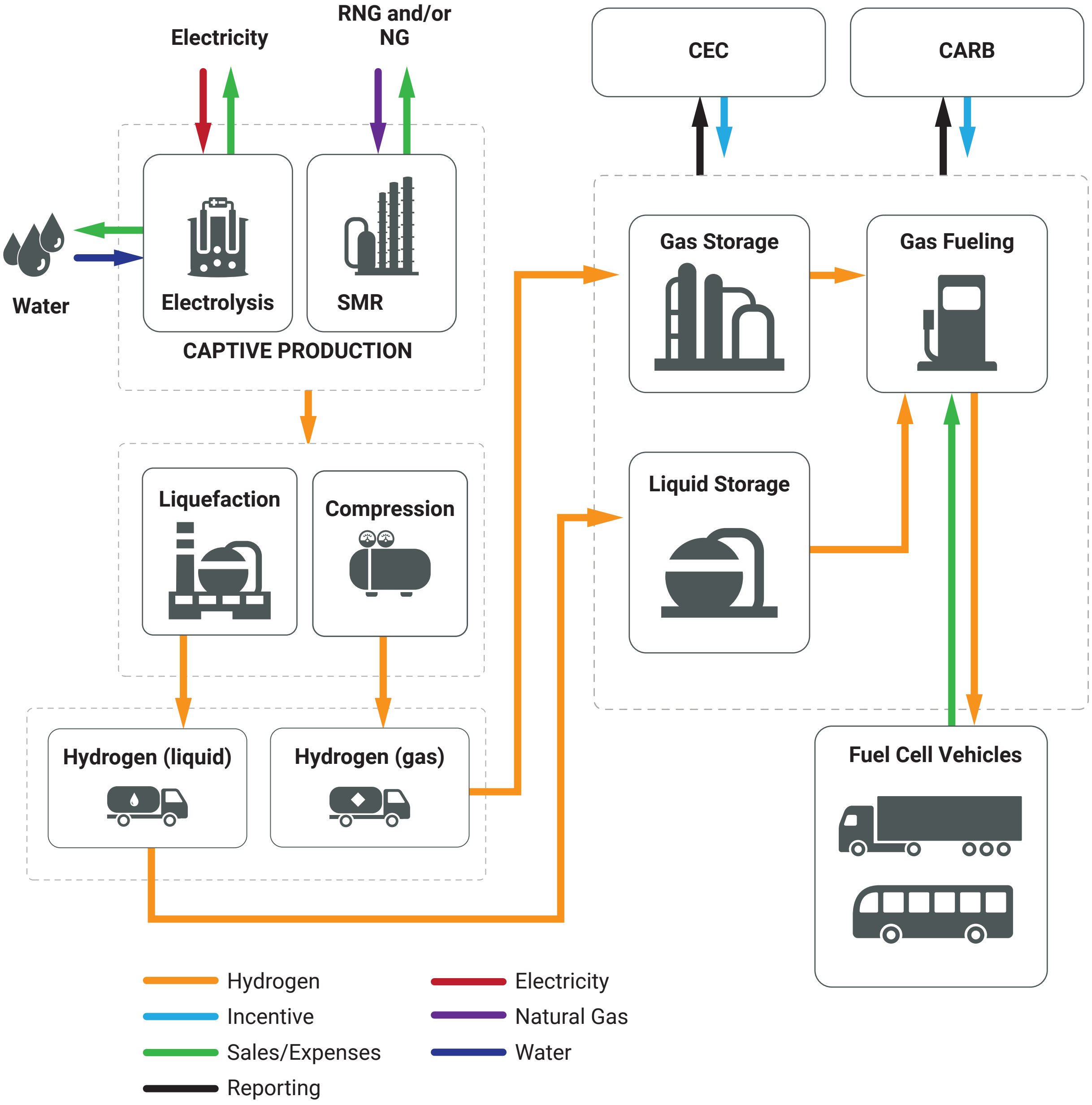
	LDVs	Mass Transit HDVs	Commercial HDVs	Aviation	Maritime	Steel	Power	Cement
Market Readiness	Commercially available but few OEMs are interested and there is little infrastructure available	Costs are relatively high compared to battery electric vehicles, but hydrogen fuel offers advantages for many fleets' duty cycles (e.g., fast refuel time)	Competitive in the 2023-27 timeframe as hydrogen fueling stations for trucking become commercially viable	Business case for aviation applications currently unproven with no available fueling stations at U.S. airports	A limited number of hydrogen fuel cell ferries are currently in operation	Experiments currently using hydrogen in blast furnaces but associative cost increases make doing so difficult in competitive market	Turbines powered by 100% hydrogen exist but are generally limited to mining purposes; still unclear which turbines under which blends can be retrofitted at minimal cost	Major cement companies have hydrogen demonstration projects with renewable electrolysis
Market Drivers	• California policies incentivize growth of hydrogen fueling stations •State Zero Emission Vehicle mandates drive adoption of vehicles with zero tailpipe emissions	• Federal loans offer a key resource for transit agencies to support low emissions vehicles and infrastructure	• Large trucks can meet most use cases for hauling purposes • At ports, trucks can accommodate long days albeit at limited capacity • New federal policies require notable improvements in vehicle fuel economies	• Europe is designing small planes expected to be commercially available in 2035 followed by larger designs in the 2040s	•Promoted by the ammonia industry and international shipping companies as means to reduce fossil fuel use	• Steel companies in Europe developing pilot projects • The Buy Clean California Act requires steel to be sold into the state below the 2021 industrial average greenhouse warming potential	• Active interest by utilities to blend hydrogen up to 20% with natural gas •Geologic storage opportunities are available for long-term hydrogen storage	• Emphasis on decarbonization for cement production from conventional coal-fired process heating • Hydrogen from SMR with CCS may have near-term cost effectiveness for cement process heating compared to renewable electrolysis
Market Barriers	• Uncertainty about the safety of gaseous hydrogen, which is stored under high pressure • Battery electric vehicles are becoming increasingly cheaper	• The development of refueling facilities limited without public funding • Bulk purchases across transit agencies required to lower purchase cost due to higher volume certainty and scale	• Costs are currently high but there is potential to reach parity with diesel trucks by 2027[85]	• There is no demand for hydrogen at U.S. airports • The country's focus is primarily on sustainable aviation fuels like biofuels	• Ammonia as a maritime fuel poses challenges for safe handling and potential for negative health effects due to its toxicity	• Carbon capture technology is more commercially viable and may reduce the near-term need for hydrogen • Electric arc furnaces meet current emissions standards which decreases the potential role of hydrogen in steelmaking	• No market compensation mechanisms currently for long-duration storage facilities • Blends over 60% require significant system upgrades	• CCS technology is more cost effective than any hydrogen application today and may reduce hydrogen demand in the near term [86] • Hydrogen applications are limited to process heating in the near term

On-road mobility is seen as the largest near-term demand growth area for clean hydrogen

Companies entering the clean hydrogen production market regularly cited the mobility sector as the business rationale for scaling up production. The broad view is that all the components are "ready to go" due to over two decades of development in fuel cell drivetrain technologies. Light- and medium-duty vehicles and forklifts are commercially available, and there are more policies supporting hydrogen's use in the mobility sector than for any other application. Interviewees see BEVs as gaining the majority of the LDV market, while noting the potential market advantage of hydrogen for HDVs.

The growth of the clean hydrogen mobility market is benefiting from a variety of state and federal policies encouraging, financing, or requiring the deployment of clean mobility options. Clean hydrogen producers routinely cited California's LCFS as a strong incentive for improving the economics of existing and planned hydrogen production facilities for supplying the California mobility market. The state's Innovate Clean Transit regulations (requiring 100 percent clean bus fleets), incentives for fueling stations under the LCFS (Figure 16), and recently enacted zero emissions vehicle (ZEV) sales requirements were also mentioned as supporting clean hydrogen deployment in the mobility sector. In addition, the Federal Transit Agency also provides direct financial support for clean bus purchases.

Figure 16: Business Model of a Mobility Fueling Station



The business model for hydrogen fueling stations depends on hydrogen supply, hydrogen vehicle demand, and state incentives. These distributors rely on hydrogen transport from captive producers or and/or trailer transport. Fueling stations can benefit from incentives under the LCFS (administered by California's Air Resources Board) and the Clean Transportation Program (administered by CEC). The carbon intensity of the hydrogen distributed at the fueling station depends on the production and transport methods.

In the mobility sector, bus transit is viewed by some as a major growth area and the right proving ground for other vehicle classes because of the high duty cycles and the availability of public funding. Hydrogen fuel cell vehicles are commercial, though few models are currently available. Three manufacturers offer light duty fuel cell vehicles in the California market—the only state with more than one public hydrogen fueling stations. Hydrogen fuel cell vehicles offer faster re-fueling than comparably priced BEVs and greater range in long-haul heavy-duty applications. This is driving interest in hydrogen bus transit, according to the interviews, which has a history of operations with compressed natural gas—a technology with a similar fueling and operational profile compared to hydrogen fuel cells.

Box 4: Fuel Cell Drayage Trucks Poised for Growth

A particularly ripe use case for hydrogen fuel cells is drayage trucks, which transport cargo containers to and from ports and railyards. Traditionally diesel-fueled with long idle times, drayage operations are notorious for degrading local air quality. The process of replacing these diesel engines with fuel cells began a decade ago when the National Energy Technology Laboratory (NETL) offered funding for Zero Emission Cargo Transport (ZECT) demonstrations.[87] Today, Kenworth and Nikola are both planning to make fuel cell trucks for drayage operations.[88]

The interviewees were less optimistic about hydrogen's ability to compete with BEVs. Battery costs are falling rapidly, driven by increased experience and knowledge with battery technology. Charge times, energy density, and safety are also improving rapidly, pushing battery electric drivetrains into heavier duty and longer distance applications that were not considered plausible just a few years ago.

Electricity producers are experimenting with hydrogen-ready turbines and hydrogen production opportunities

Interviewees described multiple opportunities to pursue clean hydrogen in the power sector. Early movers are active in using electricity to produce hydrogen, hydrogen to produce electricity, and reusing electricity-producing assets for hydrogen production. These activities are often led by power generators, guided by compelling business rationales.

Electricity production via turbine combustion—either using hydrogen blended with natural gas or pure hydrogen—is the focus of many utility-supported projects in partnership with turbine manufacturers. Technology for 100 percent hydrogen combustion already exists, albeit at a relatively small scale. In addition, significant research is underway on retrofitting existing natural gas turbines to support ever-increasing volumes of hydrogen blends.[89,90,91]

Some power plant owners expressed interest in converting their existing assets into direct hydrogen production facilities. An important technical detail is that the efficiency of electrolysis can be increased by using high temperature steam like that found in nuclear power plant thermal cycles or from hydrothermal sources. There are also firms investigating repurposing former municipal solid waste or coal facilities for hydrogen production options.

Power providers described interest in hydrogen as an avenue for avoiding power plant retirements, hoping that the addition of hydrogen revenues would help outweigh the cost of required emission reductions or the inability to compete with cheaper power alternatives solely on the price of electricity. Some independent power plant owners described hydrogen as a potential new source of revenues for their existing power plants or creating new market opportunities as emissions restrictions become more stringent. Certain investor-owned utilities see hydrogen as a long-term opportunity to meet their climate commitments. Irrespective of business model approaches, companies in the electricity industry tend to have highly skilled engineering expertise and large balance sheets, both useful for expanding into new markets.

There is investor interest in employing hydrogen as a decarbonization pathway in the industrial sector, despite not being a first mover

Absent new policy support, clean hydrogen demand growth in the industrial sector was viewed as a long-term prospect. Industrial end users such as cement, steel, and glass, and those seeking to provide these subsectors with energy and heat solutions, broadly agreed that hydrogen is a potential pathway for decarbonization. While widely acknowledging that hydrogen can be a tool to help meet decarbonization ambitions, companies representing domestic heavy industries reported almost no immediate intentions to retool their processes or pay a premium for lower carbon sources of hydrogen to meet their current chemical feedstock requirements. Many industrial stakeholders cited domestic and international price competition in commodity industries, costly and untested equipment retrofits or new-builds for assets with multi-decadal lifetimes, uncertain cost and availability of alternative options to reduce emissions (e.g., electrification or carbon capture), and little to no policy support to cover the fixed and operational cost premiums for lower emitting operations.

A key challenge for adopting clean hydrogen across heavy industry is the inherent large scale and multidecadal lifespans of industrial assets, slowing the pace of asset replacement, turnover, and—ultimately—hydrogen integration. Many heavy industrial end-use cases for hydrogen, such as steel and cement, are seen as longer-term decarbonization options, mainly due to competing pathways that are more cost efficient in the near term, and the difficulty of changing established processes that are not commercially amenable for the inclusion of hydrogen. Further, many products of heavy industry, such as steel and ammonia, are trade-exposed global commodities, making the current high cost of clean hydrogen a barrier to deployment. Without strong drivers such as policy requirements, these industries will likely wait until other sectors embrace hydrogen (or other decarbonization technologies) to reduce costs and risk.

In steelmaking, hydrogen can serve as either a chemical feedstock or heat source, depending on the type of steel production. For example, the direct reduction of iron-electric arc furnace (DRI-EAF) process, where raw materials consist of scrap steel and direct reduced iron (DRI), is the dominant production method employed in the United States.[h] Hydrogen can serve as a substitute reducing

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[h] Globally, the dominant steel production method is the blast furnace/basic oxygen furnace (BF/BOF) process, which is a coal-dependent and emissions-intensive process. However, only one-third of U.S. steel is produced using the blast furnace process, requiring alternative steel decarbonization solutions than much of the world including Europe, which does have more of a focus on steel decarbonization. In fact, increasing the share of scrap-based EAF steel production to replace emissions-intensive BF/BOF processes has been previously recommended as a decarbonization strategy.

agent in place of natural gas to produce DRI, eliminating about 40 percent of emissions from the DRI-EAF process.[92,i] Major steel companies are experimenting with integrating hydrogen into the DRI-EAF process, though these pilots have not yet reached the United States. Overall, the steel industry may be less compelled to experiment with hydrogen as a decarbonization pathway for the DRI-EAF process, especially given the clear path to electricity decarbonization for EAFs.

In contrast to steelmaking, the primary use for hydrogen in cement and glass production would be to replace fossil fuels as a heat source. Fuel switching was generally seen as the most immediate method to reduce emissions, while CCS was viewed as a method that could reduce process emissions that would not be addressed by hydrogen. In some cases, replacing fossil fuels with hydrogen for process heat would require retrofitting boilers, making it less attractive than other decarbonization options such as CCS on conventional heat production. In cement, however, the view from interviewees was fairly optimistic due to planned retrofits of commercially available facilities to inject a small percentage of hydrogen into fuel. For both glass and cement, there was not a strong view on opportunities for process emissions reductions. Hydrogen in the calcination process of cement production has been identified as a potential decarbonization pathway, though this was not the focus of cement makers interviewed.

Ammonia producers have also been actively considering the prospects of low-carbon hydrogen production as a method to reduce their emissions—both directly from production and indirectly from the ammonia value chain. Ammonia producers are motivated by their voluntary emissions reductions targets and anticipated increasing scrutiny from the European Union (EU) regarding the relative emissions of imports.[j] Further, emissions reduction goals seem to be on a decadal timescale, reducing the immediate urgency for any operational shifts. Taken together, low(er) carbon hydrogen as a decarbonization pathway for ammonia production appears to be a mid- to long-term prospect.

Aviation and maritime end uses are under exploration, primarily driven by stringent international and European emissions reduction targets and consumer pressure

Compared to light-duty and heavy-duty vehicles, other mobility industries are progressing slowly in hydrogen development, largely due to long asset lifespans and engineering timelines. Research and development in aviation and maritime transport are ongoing in the United States, as commercial aviation and maritime companies explore their options—usually hydrogen, electric, and or low carbon fuel—while considering the cost, storage, and safety requirements. For example, Airbus has announced plans to create commercially available hydrogen planes by 2035, although such models will be limited to short flights (less than 1,000 miles) due to the weight of hydrogen storage tanks.[93] In maritime applications, ammonia offers a compelling option for fueling propulsion because of its low noise levels and reduced water and air pollution. However, interviewees expressed concern about the toxicity of ammonia, particularly because crews may be isolated at sea if a toxic

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[i] Abating the remainder of emissions from the DRI-EAF process will require using renewable electricity for the EAF.

[j] Ammonia and its derivatives as fertilizer for the agricultural industry are global commodities, for which the U.S. is a major exporter.

leak occurred. Because of these concerns, many maritime end users view hydrogen and methanol as preferable alternatives to ammonia fuel. Using hydrogen as fuel for ferryboats, which have short routes, will soon be deployed.[94]

The International Maritime Organization's (IMO) standards are a critical reason why international maritime companies are looking at low carbon fuels as alternative to diesel engines. IMO also adopted standards in June 2021 to reduce carbon intensity of large ships by setting a threshold for CO_2 emissions per cargo ton and mile. Related, the organization has a goal to reach 40 percent carbon intensity reductions below 2008 levels by 2030.[95,96] IMO also has stringent global regulations in place to lower pollutants from shipping, including NO_x, SO_x, carbon monoxide (CO), and particulate matter (PM). For example, the global sulfur limit was reduced to 0.5 percent from 3.5 percent in January 2020.[97]

Airports in the United States have conducted preliminary investigations using hydrogen for ground services, including for taxiing services. Issues with hydrogen supply, terminal space, and insufficient funding for infrastructure, however, were identified as key barriers. Additionally, a significant portion of ground support has already been electrified, such as ground support equipment for fueling, towing, and loading baggage. For hydrogen to play a significant role in aviation, airlines will likely be the first movers. Airlines have emissions reduction commitments and provide general guidance to OEMs and airports; airline investment in hydrogen aviation technology would send an important signal to OEMs.

CROSS-CUTTING INDUSTRY FINDINGS

Summary: Companies are looking beyond their traditional industry boundaries to pursue clean hydrogen. Companies active in traditional and clean energy subsectors are actively exploring clean hydrogen technology and business opportunities. This diverse array of companies spoke often of working outside of corporate boundaries on demonstrations, pilot projects, and research endeavors, making **collaboration a hallmark of early clean hydrogen market activity**. These collaborations often cross the Atlantic, where **learning from regions with significant hydrogen development can accelerate U.S. market formation.**

Infrastructure and asset repurposing is a major focus of clean hydrogen investment activities. Companies and policymakers alike support uses of clean hydrogen that enable infrastructure reuse or repurposing as a means of lowering the costs of economy-wide decarbonization, avoiding stranded assets and creating value from existing assets. Examples illustrating the breadth of infrastructure reuse ambition include natural gas infrastructure carrying pure or blended hydrogen, decades-old nuclear power plants generating clean fuel for decades to come, and incumbent SMRs installing carbon capture to dramatically reduce emissions.

Specialized regional markets are emerging, shaped by existing regional resources and industries. Companies and consortia in the Texas Gulf Coast and southern California are pursuing multi-party hydrogen markets, the former focused on the region's heavy industrial base with the latter emphasizing freight shipping, portside material handling, and power generation. These regions are benefiting from **state-level policies that provide early support for hydrogen in some states**. California in particular has a series of supportive policies across the entire hydrogen production, delivery, and end use domains.

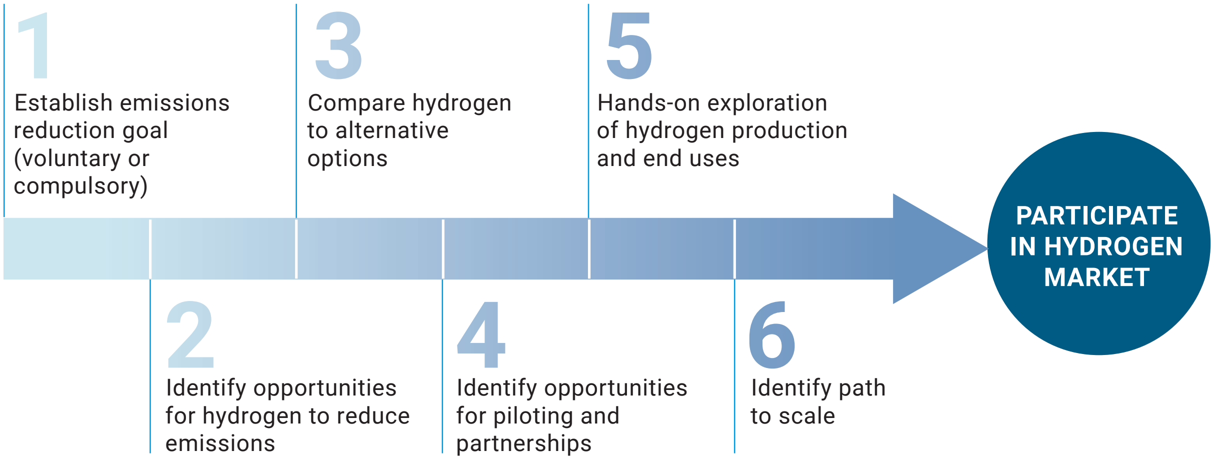
The sections that follow elaborate on these key interview findings.

Companies are looking beyond their traditional industry boundaries to pursue clean hydrogen

Companies exploring use cases, production pathways, and business opportunities for clean hydrogen span multiple economic sectors. Examples include traditional energy companies seeking a foothold in clean energy growth markets; energy-consuming companies taking a closer look at their own fuel supply options; equipment manufacturers hoping to meet and grow demand for their own products; and others that are actively devoting internal staff resources, R&D funds, and political capital to develop clean hydrogen pathways. This broad interest may reflect hydrogen's status as an energy carrier—like electricity—rather than an energy resource.

Interviews identified early activity in clean hydrogen markets from organizations as varied as data center owners, fertilizer producers, power plant turbine manufactures, transit agencies, and traditional oil and gas developers. Despite the diversity of industries and experience with clean hydrogen, there emerged a set of common milestones on the path to participate in clean hydrogen markets (Figure 17).

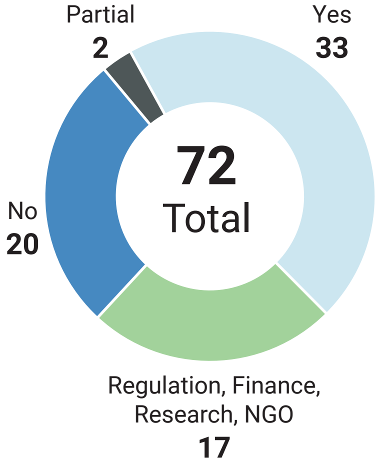
Figure 17: Common Milestones on Companies' Paths to Hydrogen Market Participation



While interviewed companies differed in their progress along this path to market participation, many discussed common milestones. The process tends to begin by establishing emissions reduction goals. Fewer companies have reached later milestones.

Companies are also exploring hydrogen production and use cases within their own market sectors through early engineering studies, internal capability and capacity building, and partnerships with established vendors or other new market entrants. Most of these companies are motivated by the prospect of capturing new growth markets, as well as their own emissions reduction targets (Figure 18).

Figure 18: Public Decarbonization Commitments Among Interviewed Organizations



Sixty percent of interviewed companies directly involved or exploring participation in the hydrogen value chain had publicly announced clear or partial decarbonization targets; many of these companies targeted to achieve net-zero emissions between 2040 and 2050. Half of the companies without decarbonization targets are smaller technology startups. Organizations dedicated to regulation, finance, and research and non-governmental organizations were excluded from this count.

Collaboration is a hallmark of early clean hydrogen market activity

There is significant uncertainty in early hydrogen market development. This uncertainty, coupled with potential opportunities and the need to ascertain and accommodate market trends, has prompted organizations to explore a wide range of technology options and business approaches. Companies are actively augmenting internal activities and strategies with consortia, partnerships, collaborations, organizations, and acquisitions across the clean hydrogen value chain. This is helping companies gain knowledge and build capabilities. Such a broad and varied focus on clean hydrogen technology and market development will undoubtedly lead to innovative technologies, policies, and business models.

In interviews, companies highlighted the nascency of new supply and demand pathways and the advanced progress of European and Asian companies as rationales for working outside of their organizational boundaries; the need to "catch up" was perceived as a motivation for remaining competitive or enhancing competitiveness in a changing marketplace. Utility industry research, mobility sector piloting, and mergers and acquisitions underscore the motivations.

Utilities with natural gas pipelines, distribution systems, and turbines are collaboratively researching the ability of these natural gas assets to accept hydrogen blends and be repurposed to operate on hydrogen alone. Over the last two years, a number of utilities have dedicated internal resources to understanding hydrogen's potential use in their existing assets, working with public institutions like the DOE's National Labs, universities, and industry associations such as GTI, EPRI, and PRCI.[98,99,100,101] These activities are helping to broaden utility capabilities, develop best practices, and share lessons learned. Most of these collaborations have connections to equivalent organizations in Asia and Europe. The reported motivations for these collaborations include vetting a potentially transformative clean energy pathway, avoiding the premature obsolescence of their existing assets, and making the case to customers and regulators that hydrogen can be safely and prudently incorporated into their energy mix.

Vehicle fleets provide another example of collaborative efforts and motivations. Bus OEMs are working in close collaboration with transit agencies to pilot and test hydrogen fuel cell buses, largely funded through public sources. Transit agencies are already seeing the benefits of piloting and testing new bus models for technology readiness and performance in the duty cycle. Drayage (moving freight short distances, for example between ships and long-haul trucks at ports) and long-haul trucking industries are also partnering with truck OEMs to pilot fuel cell vehicles. Some heavy-duty fuel cell vehicle manufactures have signed development partnerships with counterparts in Europe. Under these agreements, U.S. designs will be built in the EU, opening sales to large and more advanced markets through EU certification and providing access to testing facilities not available in the United States.[102,103]

One additional area where companies are building capabilities outside of their traditional markets to improve their prospects in the emerging clean hydrogen market is through acquisitions. Independent and corporate venture capital provides companies access to technologies, markets, and expertise from smaller companies experimenting with hydrogen, typically working on production technologies.

Learning from regions with significant hydrogen development can accelerate U.S. market formation

Companies with interests across the clean hydrogen value chain often referenced Europe's leadership on clean hydrogen policy, technology, and business models. Many companies see market activity outside the United States as a strategic benefit to cost-effective clean energy deployment in this country.

Europe's experimentation with policy approaches to incentivize these new industries are informing the U.S. policy landscape. Companies noted that hydrogen market activity in Europe is a decade ahead of the U.S. market, spurred by the combination of generous government financial support for early-stage projects, stringent sector-specific deployment and emissions targets (especially in the mobility sector), and corporate and government emissions reduction targets.[104] Several companies compared today's clean hydrogen deployment in Europe to wind and solar deployment in the past decades; Europe was at the forefront of implementing policies, some costly, to stimulate demand for clean electricity generation from wind and solar, driving costs down for the rest of the world.

Many companies see the monitoring and understanding of activities in Europe as important for understanding of the practicalities, economics, and business arrangements for clean hydrogen. Domestic industrial companies that would face costly and uncertain retrofit requirements for moving to clean hydrogen processes highlighted the advantages of analyzing the real-life performance of alternative processes and equipment of first movers in Europe—many supported by government funding at a scale not currently available in the United States. Companies also discussed the value of observing emerging business models, including those supporting hydrogen hub formation. Clean hydrogen deployment in Europe is, however, nearly entirely focused on pathways that use clean electricity to produce hydrogen; the economies of scale and other findings from early deployment will not benefit other production pathways equally, especially not those relying on natural gas.

Many U.S.-based companies have sought to forge partnerships with European counterparts, sending emissaries to learn firsthand or entering business partnerships piloting new technologies both in the United States and abroad. Others have employees based in Europe whose job responsibilities include reporting back to U.S. colleagues on clean hydrogen progress. Some of these companies are also participating in international workshops facilitated by think tanks.

Box 5: International Hydrogen Hub Development Can Inform U.S. Hydrogen Policy & Business Models

The United States can analyze operational or developing hydrogen hubs in Europe and Australia to gain policy, technology, and business model findings. Across Europe, hydrogen hubs are being developed as part of the broader European Hydrogen Backbone (EHB), which plans to span 23 gas infrastructure companies and 21 countries to create an integrated hydrogen infrastructure network.[105] The EHB relies heavily on repurposing natural gas pipelines; a recent report on the backbone's plan found that 69 percent of the hydrogen network could consist of repurposed natural gas networks by 2040.[106] Smaller hubs ("hydrogen valleys") are targeted by the European Commission to decarbonize islands and remote areas. These hubs are expected to be used for industrial heat, transport, electricity balancing, and space heating for residential and commercial buildings.[107]

In the United Kingdom, the Northern Endurance Partnership—a public-private partnership—plans to construct a CCS/hydrogen hub in the Humber region.[108] The Humber cluster would be anchored by a blue hydrogen plant, led by Equinor, at a chemical production facility. This project plans to eventually use offshore wind to produce hydrogen. The United Kingdom government has supported the hydrogen and CCS cluster with over US$80 million in grants.[109] The Humber cluster leverages the region's large industrial emitters, proximate geologic formations for storing CO_2, and supportive government to catalyze an industrial transition.

In Australia, National Energy Resources Australia (NERA) has formed 13 hydrogen clusters by "providing seed-funding in partnership with governments and industry to build the skills, capability and commercialization opportunities in the emerging hydrogen industry."[110] Regional hydrogen hubs are a critical part of Australia's Hydrogen Roadmap. Hubs are seen as a way to reduce costs, promote economies of scale, foster innovation, and promote synergies from coupling sectors.[111] The roadmap estimated that 7,600 jobs could be created and about US$8.2 billion a year could be added to the GDP by 2050 in a "cautiously optimistic scenario."[112]

Infrastructure and asset repurposing is a major focus of clean hydrogen investment activities

Companies and policymakers are interested in clean hydrogen uses that support infrastructure reuse or repurposing that could lower the costs of economy-wide decarbonization and maximize the use of existing assets. Infrastructure reuse strategies are under active consideration across the full production, transport and storage, and end use value chain.

Owners of natural gas infrastructure and end uses are actively researching the potential of clean hydrogen for extending the useful life of their existing systems. Blending hydrogen with natural gas in pipelines and turbines is one example. Companies and the DOE are funding various studies evaluating pipeline suitability, necessary upgrades, and safety of blending relatively low amounts of hydrogen into existing interstate pipelines, gas distribution systems, and gas turbine power plants.[113]

On the upstream side of the supply chain, owners of existing hydrogen production facilities are exploring options for reducing emissions from their hydrogen production. Steam methane reformers convert natural gas to hydrogen at large industrial facilities, which are also significant sources of greenhouse gas emissions. Adding carbon capture to these facilities can dramatically lower their emissions (repurposing existing capital, facilities, and expertise) and supply relatively clean hydrogen at large scale and lower costs compared to other clean hydrogen production pathways like electrolysis in the near term (Figure 5). Another alternative with lower capital costs but higher feedstock costs is using RNG in hydrogen production facilities currently using fossil gas. RNG comes from a variety of agricultural and municipal waste sources and is typically considered near or below zero emissions, meaning hydrogen it produces can be considered clean even without capturing the emitted CO_2. Owners of existing hydrogen production facilities are actively investigating these pathways.

Specialized regional markets are beginning to emerge, shaped by a regions' existing resources and industries

Several companies and consortia are actively developing hydrogen hubs—clusters of clean hydrogen supply and demand at strategic locations in the country to reduce emissions, achieve economies of scale, diversify risk and revenues, and share costs. Each hub has its own special character, shaped by existing resources, infrastructure, and industries. Companies and policymakers are looking to Europe's progress on this hub approach to inform clean hydrogen market formation. Several locations for hub formation are under consideration; the Texas Gulf Coast and southern California appear to be the most advanced.[114,115,116]

Several desirable attributes for hydrogen hub locations are starting to emerge. The most fundamental is the co-location of companies interested in developing clean hydrogen supply and demand, ideally near-term scalable demand with a diversity of use cases in the long term. Supporting infrastructure and suitable geography are also critical, including electricity transmission, multi-modal transport options, CO_2 pipelines, and proximity to hydrogen and CO_2 storage locations. Lastly, a supportive policy and regulatory environment is viewed as key, including incentives for companies to lower their emissions and the regulatory framework to enable them to do so using hydrogen.

Several companies in the Texas Gulf Coast—home to the largest collection of refineries and industrial facilities in the nation—are working to develop clean hydrogen business relationships.[117,118] Low electricity prices, adequate electricity transmission access, existing hydrogen pipelines and producers, and a range of current and potential hydrogen end users make the region well positioned to be an early clean hydrogen market hub.

The region including the Los Angeles/Long Beach Port—the largest in the nation—is also an area of active hydrogen business activity. California is home to all but one of the nation's 48 commercial hydrogen vehicle refueling stations.[119] The Port is investigating hydrogen for drayage and material handling, and local fueling infrastructure could support heavy duty trucks transporting goods out of the port to their final destinations.[120] Several refineries in the area are also potential consumers of clean hydrogen. Supportive policy in California, including the LCFS and 2035 and 2045 zero-emissions vehicle mandates, are anticipated to add additional tailwinds for hydrogen market formation in the region.[k]

State-level policies are providing early support for hydrogen

Some states have taken bold action to promote clean energy pathways that include hydrogen as part of a low-carbon economy. In some cases, these policies affect national markets, creating potential incentives for producers in other states. California, for example, has three policies that have attracted attention to hydrogen as a fuel of the future: the LCFS, the Zero Emission Vehicle (ZEV) mandate, and support for hydrogen fueling infrastructure.[121] Other states have taken actions to integrate hydrogen into natural gas systems and enable CO_2 storage in the state.

The LCFS—administered by the California Air Resources Board (CARB)—provides incentives for low carbon fuels producers (Figure 18) and is viewed as providing strong economic support for existing and planned hydrogen production facilities that sell into the California market. The price of credits sold under the LCFS program is seen as sufficiently high and stable to spur investment. Long-term price uncertainty can weigh on an investment decision, from both the project developer and private and tax equity perspectives.

Some important context mentioned in the interviews is California's ZEV regulations. In place since 1990, the ZEV regulations were recently updated to create a path to 100 percent ZEV adoption by 2035 for several vehicle types under the Advanced Clean Cars program.[l,122] The ZEV mandate also includes $20 million in funding per year to build at least 100 hydrogen fueling stations; there are currently 47 hydrogen fueling stations in the state today.[123,124] California's rapid adoption timeline for ZEVs is ambitious compared to market adoption over the last 10 years.[125,126] Developing corresponding infrastructure for electric vehicles, hydrogen-powered vehicles, and other ZEVs is seen as a challenge for meeting local fire codes; this has the potential to delay infrastructure build-out. Several other states follow California's vehicle adoption standards, creating an even larger market for ZEV adoption and associated infrastructure.

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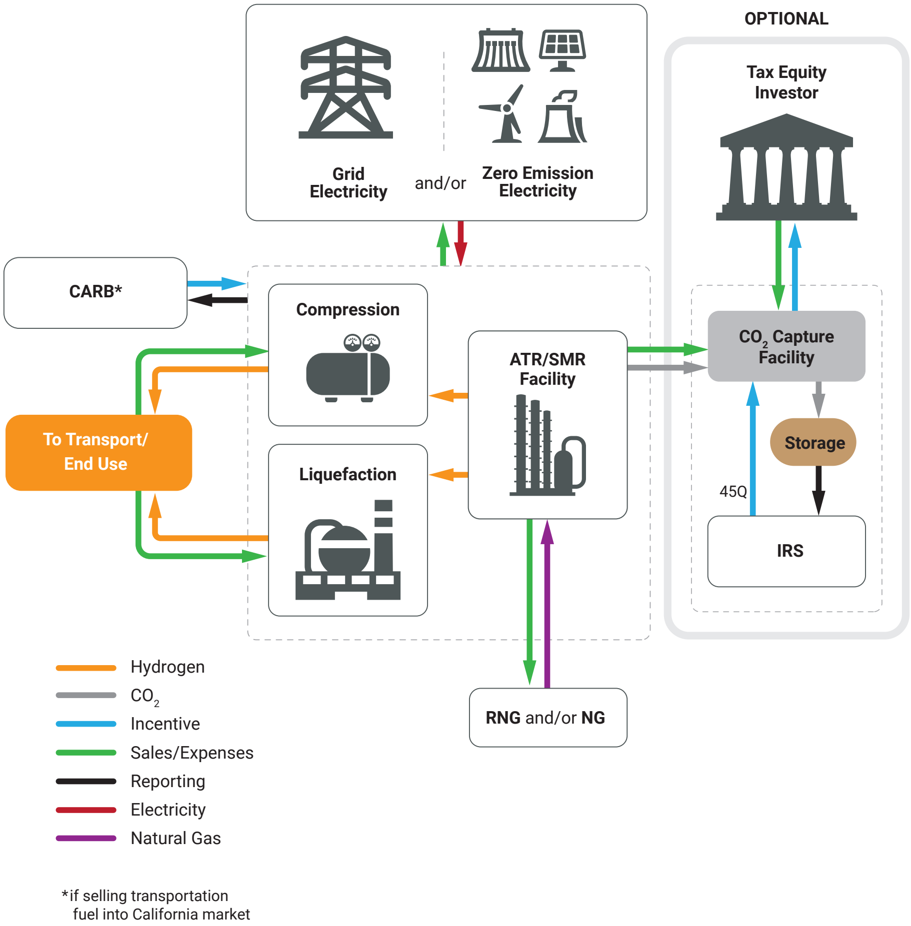
[k] California is targeting 100% of new sales be zero-emission vehicles by 2035 for passenger cars and trucks, 2035 for drayage trucks and equipment carriers where feasible, and 2045 for medium- and heavy-duty vehicles where feasible.

[l] California is targeting 100% of new sales be zero-emission vehicles by 2035 for passenger cars and trucks, drayage trucks, and off-road vehicles and equipment where feasible. It is targeting 2045 for medium- and heavy-duty vehicles where feasible.

Another regional policy that was mentioned in multiple interviews is Oregon's state bill SB98, that supports utility use of RNG. SB98 includes hydrogen derived from renewable energy resources in its definition of eligible types of RNG, sets a goal for integrating RNG into the gas supply, and allows utilities to pay incrementally more for qualified fuel.[127] The new standard sets a goal to increase the amount of RNG in the fuel mix to 30 percent by 2050. Industry with operations in Oregon identified SB98 as a transformational tool for enabling clean hydrogen; before its passage, gas utilities had difficulty justifying higher payments for cleaner fuels, similar to issues faced by electric utilities seeking to justify paying more for renewable energy absent renewable portfolio standards.

Figure 19: Business Model of SMR/ATR With and Without CCS Selling Hydrogen into the California Market



The business model for hydrogen producers relies on end users, supply of natural gas (either renewable or fossil gas), electricity (either zero emission or bulk supply), and, if applicable, carbon dioxide transport and storage and public incentives. The hydrogen producer can leverage incentives from the LCFS, operated by CARB, when selling into California markets for an additional revenue stream. The carbon intensity of these hydrogen producers depends on the upstream emissions and production method of natural gas, the use of zero emission electricity, and the capture and storage of CO_2*.*

Appendix A – Interview Method

The scope of the interviews was determined based on a literature review of the current and emerging hydrogen value chain and augmented by recommendations from interviewees.

In this study, a qualitative social research approach, employing a semi-structured interviewing method coupled with snowball (referral) and theoretical sampling was used as the basic methodology to gather practitioner perspectives. A semi-structured interview is an open knowledge sharing approach, where information is conveyed in a conversational, free-flowing manner. The conversation is guided by a set of themes and ideas outlined in the form of questions by the interviewer. The loose but intentional structure of this approach allows for ideas to surface naturally and provides multiple opportunities for the interviewees to express themselves and offer depth of insight on one or multiple subjects. As such, a richer perspective on a matter is shared with the interviewer, and the interviewee is less stressed doing so, as the latter can choose how to convey thoughts and ideas. Further, in terms of both a broader study of a phenomenon and specifically as a methodology, semi-structured interviewing is benefitted by triangulation, where multiple views on the same subject are sought to minimize single method, single theory, single observer biases.

The next step was to identify entities publicly involved in hydrogen activities across the value chain. This was initially informed by market research and discussions with hydrogen industry experts. Additional potential participants were identified through referrals from industry practitioners.

The set of interviewees covered the breadth of the value chain, including multiple actors actively participating, investing and/or analyzing hydrogen production, transport and storage, and end-use. A database of over 300 potential interviewees was created, which is non-public and handled in accordance with a moderate risk classification for data.[128] 142 individuals were contacted for interview yielding 72 interviews (Table 7) during between April and July 2021. Most interviews (49/72) were conducted with a single organization representative, while the remainder had multiple interviewees attend and participate.

Table 7: Number of Interviews Conducted by Sector

Sector	Policy/ Regulation	On-Road Transport	Aviation and Maritime Transport	Buildings	Utilities	Industrial Use	Production	Finance	Total
# of Interviews	5	14	9	7	8	10	9	10	**72**

GUIDING QUESTIONS FOR INTERVIEWS

Topics covered

1. Microlevel: firm value proposition and supporting business model
2. Macrolevel: technology, substitutes, competition, partnerships
3. Cross-cutting: policy/regulatory/economic/finance/insurance/social license
4. What-if/Scenarios: sector-coupling, stroke-of-pen, in-directs, etc.
5. Black Swans & Magic Wands

Preamble

The purpose of this interview is to understand:

1. Firm position within the hydrogen landscape, including current value proposition(s) and supporting business models
    a. Partners, activities, resources, channels, customers, cost structure, revenue structure
2. Decisions and information considered that led to #1 (if not obvious)
3. Situational analysis: broader overview of hydrogen upstream & downstream of the firm and interfaces with other sectors of the economy
4. Where to from here, why, and how? Projects, pilots, trials, initiative, etc.
    a. Needs & wants; barrier & opportunities

Section 1: Microlevel: Business Model

1. Take me through what your offerings are with respect to hydrogen and where you fit within the broader value chain.
    a. [Interviewer note: update the question based on firm role: producer, supplier, consumer, regulator, investor, etc.]
    b. [Interviewer note: be sure to cover all the business model elements: partners, activities, resources, channels, customers, cost structure and revenue structure as appropriate]
2. To what extent have your offerings changed over time? Why is this so (or not)?
3. How do you see your business changing in the next short (12-36 month) and long term (before 2030)? Tell me about why you think this way.

Section 2: Macrolevel: Broader Hydrogen Value Chain

1. How would you assess the current hydrogen landscape in the United States?
2. Where do you see the most activity across the landscape? Why? Where are areas of relative stability? Why?
    a. [Interviewer note: same as above; use the guide to cover the various links in the chain]
3. Do you see regional differentiation within the hydrogen value chain in the US? Hubs of production? Transport? End uses? Why/why not?
4. How might substitutes & complements affect the landscape?
    a. [Interviewer note: dependent upon interviewee; might explore CCS, long-term storage, EVs, etc.]

Section 3: Cross-cutting: policy/regulatory/economics/finance/insurance/social license

1. The United States does not have a national hydrogen policy like other countries such as Japan, Australia, Germany, and Canada. Does it need one? Why or why not?
2. Are there any policies or regulations that sit adjacent to hydrogen that have first order effects on your firm? (e.g., EPA Title V, DOT PHMSA, DOT Corporate Average Fuel Economy (CAFE), “Buy American” mandates, etc.)
3. To what extent is access to capital and/or access to insurance a bottleneck? What are your sources of capital?

Section 4: What-if /Wand/Swan

1. If you had a magic wand, what would you change to:
    a. Enhance the prospects of your firm vis-à-vis hydrogen?
    b. Enhance the prospects for hydrogen in general? Please explain.
2. What are circumstances that would either 0.1X or 10X your firm’s prospects regarding hydrogen in the next 5 years? Please describe these black swans.
3. Now that we have been talking about the present and future of hydrogen for almost an hour, what questions are you most interest in exploring more? Put another way, if you were to direct my research, where would you point me next?
    a. Finally, who else do you recommend I speak to about any topic we discussed

Appendix B – Data Assumptions

Table 8 and Table 9 summarize the assumptions made by various sources when developing cost and emissions figures used to generate the graphs in Figure 5.

Table 8: Costs Sources and Assumptions

Source	SMR		Coal Gasification		Electrolysis		
	No Capture	90% Capture	No Capture	90% Capture	US Grid	Nuclear	Renewable
Columbia[129]	Cost: $1.05-1.50/kgH2 Assumptions: Gas: $3.50/MMBtu	Cost: $1.71-2.15/kgH2 Assumptions: Gas: $3.50/MMBtu	No data provided	No data provided	Cost: $4.50-6.04/kgH2 Assumptions: Capacity factor: 90%, Electricity: $60-90/MWh	No data provided	Cost from Solar: $7.00-8.00/kgH2 Solar Assumptions: Capacity factor: 20%, Electricity: $36-46/MWh Cost from Wind: $4.80-7.25/kgH2 Wind Assumptions: Capacity factor: 35%, Electricity: $40-60/MWh
DOE[130]	No data provided	No data provided	No data provided	No data provided	Cost: $4.37-6.27/kgH2 Assumptions: CapEx: $1000-1500/kW, Efficiency: 60%, Capacity Factor: 90%, Electricity: 5-7 c/kWh	No data provided	Cost from Solar: $5.54-6.09/kgH2 Solar Assumptions: CapEx: $1000/kW, Efficiency: 60%, Capacity Factor: 33%, Electricity: $30/MWh Cost from Wind: $4.22-5.76/kgH2 Wind Assumptions: CapEx: $1000/kW, Efficiency: 60%, Capacity Factor: 38-52%, Electricity: $33/MWh

(continued next page)

Source	**SMR**		**Coal Gasification**		**Electrolysis**		
	No Capture	**90% Capture**	**No Capture**	**90% Capture**	**US Grid**	**Nuclear**	**Renewable**
E3[131]	Cost: $1.30/kgH2 Assumptions: Unspecified	Cost: $1.95/kgH2 Assumptions: Unspecified	No data provided	No data provided	No data provided	Mitsubishi Hitachi Power Systems Americas, Inc. (MHPS) Cost: $5.00-5.00/kgH2 Assumptions: CapEx: $600/kW, excl. additional costs, Efficiency: 70% University of California at Irvine (UCI) Cost: $5.40-5.40/kgH2 Assumptions: CapEx: $1124/kW, excl. additional costs, Efficiency: 70%	Mitsubishi Hitachi Power Systems Americas, Inc. (MHPS) Cost: $3.10-3.95/kgH2 Assumptions: CapEx: $600/kW, excl. additional costs, Efficiency: 70% University of California at Irvine (UCI) Cost: $3.85-5.00/kgH2 Assumptions: CapEx: $1124/kW, excl. additional costs, Efficiency: 70%
ETC[132]	Cost: $0.70-2.20/kgH2 Assumptions: Gas: $1-10/MMBtu	Cost: $1.30-2.90/kgH2 Assumptions: Gas: $1-10/MMBtu	No data provided	No data provided	No data provided	No data provided	No data provided
IEA-The Future of Hydrogen[133]	Cost: $1.00/kgH2 Assumptions: CapEx: $910/kW, OpEx: 4.7%, Efficiency: 76%, CO2 T&S: $20/tCO2, Gas: $3.3/MMBtu	Cost: $1.50/kgH2 Assumptions: CapEx: $1680/kW, OpEx: 3.0%, Efficiency: 69%, CO2 T&S: $20/tCO2, Gas: $3.3/MMBtu	Cost: $1.05/kgH2 Assumptions: CapEx: $2670/kW, OpEx: 5.0%, Efficiency: 60%, CO2 T&S: $20/tCO2	Capex: $2780/kW, Opex: 5.0%, Efficiency: 58%, CO_2 T&S: $20/t$CO_2$	No data provided	No data provided	Cost: $2.50-6.00/kgH2 Assumptions: CapEx: $900/kW, OpEx: 1.5%, Efficiency: 64%
IEA-Website[134]	No data provided	No data provided	Cost: $1.90-2.50/kgH2 Assumptions: CapEx: $2672/kW	Cost: $2.10-2.60/kgH2 Assumptions: CapEx: $2783/kW	No data provided	No data provided	No data provided
IRENA[135]	No data provided	Cost: $1.50-2.20/kgH2 Assumptions: Gas: $3-3.8/MMBtu	No data provided	Cost: $1.80-2.00/kgH2 Assumptions: Coal: $1.5-3.8/MMBtu	No data provided	No data provided	Cost from Solar: $3.30-6.80/kgH2 Solar Assumptions: CapEx: $840/kW, Capacity Factor: 26%, Electricity: $18-85/MWh Cost from Wind: $2.70-5.00/kgH2 Wind Assumptions: CapEx: $840/kW, Capacity Factor: 48%, Electricity: $23-55/MWh

Table 9: Emissions Sources and Assumptions

Source	SMR		Coal Gasification		Electrolysis		
	No Capture	**90% Capture**	**No Capture**	**90% Capture**	**2017 US Grid**	**Nuclear**	**Renewable**
ETC[136]	No data provided	Emissions: 0.4-3.9 (mean 0.9) kgCO2/kgH2 Assumptions: Varies by upstream leakage rate: 0.05%, 0.2%, 1.5%	No data provided	No data provided	No data provided	No data provided	No data provided
IEA-The Future of Hydrogen[137]	Emissions: 9.0 kgCO2/kgH2 Assumptions: Unspecified	Emissions: 1.0 kgCO2/kgH2 Assumptions: Capturing feedstock related CO2 and fuel CO2	Emissions: 19.0-20.0 kgCO2/kgH2 Assumptions: Unspecified	Emissions: 2.0 kgCO2/kgH2 Assumptions: Capturing feedstock related CO2 and fuel CO2	No data provided	Emissions: 0.0 kgCO2/kgH2 Assumptions: Unspecified	Emissions: 0.0 kgCO2/kgH2 Assumptions: Unspecified
IRENA[138]	Emissions: 9.5 kgCO2/kgH2 Assumptions: Energy and process emissions only	No data provided	Emissions: 22.5 kgCO2/kgH2 Assumptions: Energy and process emissions only	Emissions: 2.3 kgCO2/kgH2 Assumptions: Unspecified	No data provided	No data provided	No data provided
RFF[139]	No data provided	No data provided	No data provided	No data provided	Emissions: 21.0 kgCO2/kgH2 Assumptions: 2017 U.S. grid mix	No data provided	No data provided
RMI[140]	Emissions: 8.0-12.0 kgCO2/kgH2 Assumptions: Unspecified	Emissions: 0.8-1.2 kgCO2/kgH2 Assumptions: Unspecified	Emissions: 18.0-20.0 kgCO2/kgH2 Assumptions: Unspecified	Emissions: 1.8-2.0 kgCO2/kgH2 Assumptions: Unspecified	Emissions: 21.0 kgCO2/kgH2 Assumptions: 2017 U.S. grid mix, Electricity: 50-55 kWh/kgH2	No data provided	No data provided

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