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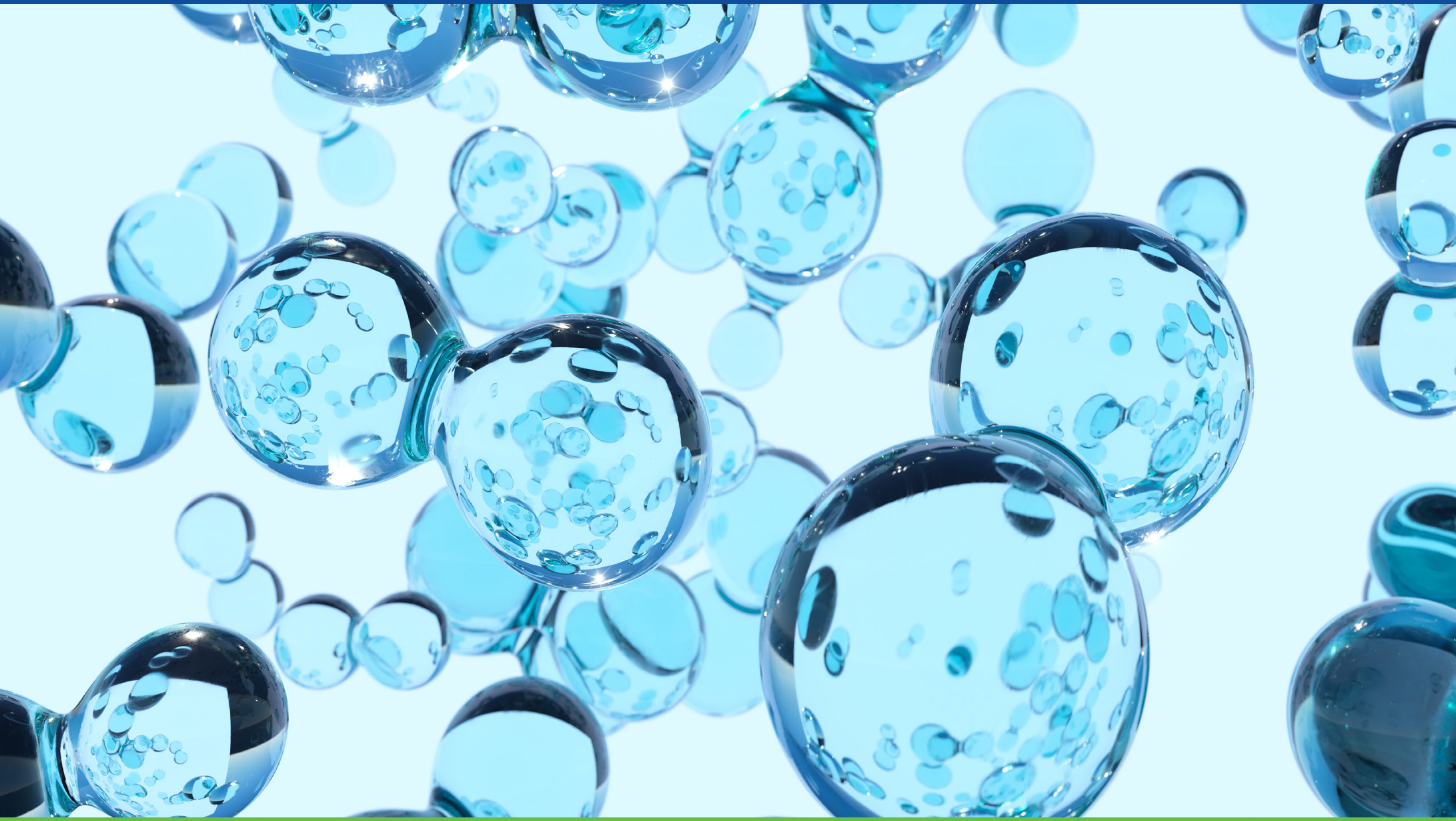

DEVELOPING A ROBUST HYDROGEN MARKET IN TEXAS

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Executive Summary

The reduction of energy's carbon footprint is a driving force in energy transitions — one that is not without its challenges. In particular, the roles of *legacy* and *scale* are central and place a hyperfocus on incumbent industries to play a critical role. The role of *technology* is also central, and its impact will increase to the extent that it is integrated into existing energy systems to decarbonize and promote reliable, secure, cost-effective options for delivering energy services.

The centrality of legacy, scale, and technology means that the decarbonization of hydrocarbon supply chains will ultimately play a part in any long-term, low-carbon energy strategy. The success of any commercial venture in any industry depends on coordination throughout supply chains and the minimization of costs to promote affordability; ventures that fail to recognize the economic hurdles associated with deployment costs and the inherent value embedded in the sunk costs of legacy assets risk falling into the proverbial "valley of death." Thus, there is an opportunity to leverage existing infrastructure. Hydrogen provides a potential platform for decarbonization that can leverage legacy to achieve scale and promote the integration of new production, and potentially end-use technologies. One of hydrogen's biggest strengths is its diversity. It can be produced in a number of different ways — including steam-methane reforming, electrolysis, and pyrolysis — so it can leverage a variety of comparative advantages across regions. Its expansion as an energy carrier[1] beyond its traditional uses in industrial applications will depend heavily on 1) significant investment in infrastructure and 2) well-designed market structures with appropriate regulatory architectures. A lack of either will risk coordination failure along hydrogen supply chains and, thus, threaten to derail any momentum that may currently be building.

Fiscal incentives are helpful for stimulating investment, particularly when the commercial prospect is otherwise insufficient. Recent federal action (i.e., the 2021 Infrastructure Investment and Jobs Act and the 2022 Inflation Reduction Act) explicitly targets a *necessary* condition for market development — infrastructure and hub development — but it is not *sufficient*. Appropriate regulatory and market design is also needed to achieve the scale required for a liquid market to emerge around hubs. To successfully generate the scale needed for broad hydrogen adoption, policy must take a full value chain approach. Barriers to permitting and siting infrastructure and market structures that do not promote price and volume transparency can limit investment and prohibit the development needed to reach the sufficient scale for a meaningful impact.

The extent to which hydrogen markets expand across the U.S. will depend on regional comparative advantages and federal, state, and local policy frameworks. Policy is currently hyper-focused on stimulating the production of hydrogen, largely through loan guarantees, grants, and subsidies, with stimulus for demand, storage, and commodity transportation coming in a distant second, third, and fourth, respectively. This will tend to drive greater capital investment to the most heavily subsidized parts of the hydrogen supply chain. This will eventually yield binding constraints on the unsubsidized parts of the supply chain. If prices are transparent and investment is unimpeded by other policies and/or regulations, then market participants will respond to price dislocations that arise with constraints by investing along the supply chain to capture value. But if transparency is absent, investment is otherwise impeded, and/or hydrogen adoption in end-use is slow to respond, market participants will not see value and therefore will not invest. So, there must be alignment between policy support and market forces, i.e., a full value chain approach. Policy that supports demand growth for low-carbon hydrogen in large-scale applications, such as industrial uses, could create demand pull that would be more favorable for supply chain development, especially if transparency in the nascent market is emphasized.

Hydrogen hubs have emerged as central to the future of hydrogen markets. A hub provides liquidity and de-risks market participation, two key functions for a market. The existence of physical infrastructure is necessary, but not sufficient, to ensure that hub services can emerge. So, while the recent federal policy emphasis on infrastructure investment is helpful, market design must also be addressed to ensure long-term growth.

Texas is well-situated to lead in hydrogen market development, given its existing comparative advantages. These include:

1. A robust industrial sector, especially in petroleum products, chemicals, plastics, and rubber manufacturing (13.2% of U.S. GDP in these sectors, collectively, in 2021) co-located with the nation's largest regional port capacity.
2. An existing hydrogen market with two-thirds of U.S. hydrogen transport infrastructure.
3. An investment environment that is generally supportive of infrastructure development.
4. A large natural gas production, transport, storage, and end-use footprint (accounting for 60.5% of U.S. GDP in oil and gas extraction and 24.6% of U.S. GDP in pipeline transportation in 2021).
5. Excellent geology for long-term storage of hydrogen and CO_2.
6. Deep expertise in logistics and supply chain management (accounting for 11.6% of U.S. GDP in wholesale trade and 10.0% of U.S. GDP in transportation and warehousing).

How the state leverages these strengths through local policy measures and market design, alongside federal government incentives, will determine the role Texas ultimately takes. Although the Texas Emission Reduction Plan (TERP) provides multiple incentives for hydrogen adoption, they are primarily focused on transportation and refueling infrastructure. As such, the state's existing incentives do not necessarily match its comparative advantages for hydrogen market development. Moreover, since they do not take a full value chain approach, they do not adequately support scale. Policies that support infrastructure investment along the entire supply chain and encourage competition and transparency could catalyze hydrogen market expansion. To that end, the history of the

U.S. natural gas market carries some important lessons regarding the roles of infrastructure investment and market structure in promoting market liquidity, which is seminal for hub development.

To be clear, policymakers should consider expanding the eligibility of hydrogen in existing TERP incentives to promote new production technologies, new end-uses, and new infrastructures for hydrogen market growth. But TERP is not a panacea. There are other areas where policy can play a role, including but not limited to 1) establishing a regulatory framework that promotes transparency and competition in pipeline operation and utilization; 2) streamlining permitting for hydrogen projects and related supply chain infrastructures; 3) encouraging pilot and demonstration projects to learn where economies of scale and other cost-saving gains can be made; and 4) adopting transparency measures that establish frequent reporting mechanisms for hydrogen storage and allow for better accounting of demand.

In Texas, converting current industrial uses of hydrogen to low-carbon production technologies is likely the most expedient, near-term path to broader hydrogen use. The opportunity for market growth and hub development can then be enhanced to the extent that heavy-duty transportation applications and other new or emerging uses can benefit from the build-out of large, backbone infrastructures needed for industrial-scale applications. Texas is in a very advantageous position to play a leading role in driving hydrogen market growth, but the evolution of policy and market structure will dictate whether or not this comes to pass.

Table of Contents

I. Introduction

The existing energy ecosystem that sustains economic activity around the world is 70% larger today than it was 30 years ago, and it is heavily dependent on coal, oil, and natural gas. In fact, all fossil fuels combined accounted for over 82% of total global energy use in 2021 — a number little changed since 1990 when they accounted for 87% of total energy use. Even as the share of electricity has increased from 31.1% to 42.4% since 1990, fossil fuels have remained a staple of total energy use. Moreover, global energy use today only serves about 6.9 billion of the 8.0 billion people on the planet, and a good portion of the 6.9 billion who are served are not served reliably. So, the scale of the energy problem demands a portfolio of innovative solutions. Hydrogen can play a major role in that portfolio.
The world is racing to develop hydrogen economies; recognizing the vital role hydrogen can play and its tremendous potential in enabling decarbonization as the energy transition progresses, countries across the globe are creating and advancing national hydrogen strategies and roadmaps. Notably, the creation of hydrogen hubs is a popular approach in many regions, driven by both industry and policymakers. Examples include the Edmonton Region Hydrogen Hub in Canada, Australia's Clean Hydrogen Industrial Hubs Program, the Port of Rotterdam in the Netherlands, and HyNet North West in the U.K., to name a few.

For the United States, the Infrastructure Investment and Jobs Act (IIJA),[2] also called the Bipartisan Infrastructure Law, was signed into effect in November 2021 and provides a total of $9.5 billion in funding to support the research and development of clean hydrogen and achieve the "Hydrogen Shot" — the U.S. Department of Energy (DOE)'s aim to reduce the production cost of hydrogen to $1 per kilogram (kg) of hydrogen by 2031. Section 813 of the IIJA authorized $8 billion in funding to support the development of at least four regional clean hydrogen hubs. The hubs are to have three purposes: 1) to help achieve the clean hydrogen production standard target of 2 kg of CO_2 per kg of hydrogen produced; 2) to demonstrate the clean hydrogen value chain from production to end-use; and 3) to create the potential for a national clean hydrogen network. The bill lays out several criteria to be considered in the selection of hub locations, including diversity in feedstock, end-use, and geography; whether the site is a natural gas-producing region; and potential employment opportunities.

The IIJA's aims to decarbonize energy systems were bolstered by the Inflation Reduction Act (IRA),[3] which was signed into law in August 2022. The IRA lays out provisions of support for renewable electricity, energy storage, environmental justice efforts, nuclear power, carbon capture and direct air capture, biodiesel and renewable diesel, sustainable aviation fuels, low-carbon hydrogen production, energy efficiency in residential and commercial buildings, and clean vehicles and refueling infrastructure. It also lays out provisions that encourage carbon capture deployment and the adoption of renewables in rural and agricultural communities; the use of nature for CO_2 reduction; and support for loans and grants that fund affordable housing and climate change mitigation strategies, in addition to providing funding for resilience measures in coastal regions and other areas of need.

Together, the IIJA and IRA support a number of climate and energy priorities at the federal level that should incentivize infrastructure development. When it comes to hydrogen, specifically, there is ample support for growth. However, as we will argue below, the support — while explicitly aimed at a *necessary* condition for market development — is not *sufficient*. Achieving the scale needed for a liquid market to emerge — particularly around physical and financial hubs — will also require a redesigned and appropriate regulatory architecture.

The Texas Gulf Coast boasts significant advantages in serving as a hydrogen hub. The region has a rich network of existing assets and infrastructure. As the nation's largest hydrogen producer, Texas already has an established hydrogen industry, with petrochemical feedstock as its main end-use. Over 60% of the hydrogen pipeline network in the U.S. is in Texas. The state also has access to abundant renewable and natural gas resources and existing and potential underground storage capacity. In addition, it hosts several industries that are critical to the acceleration of hydrogen development — including shipping, petrochemicals, and carbon capture, utilization, and storage (CCUS) — and is home to a skilled energy workforce.

Notably, there are a number of potential ancillary benefits associated with hydrogen. For one, hydrogen used in place of hydrocarbon energy sources improves local air quality by eliminating particulates, as well as sulfur-based pollutants. In addition, the diversity of hydrogen production technologies allows a large number of energy supply sources to be used as feedstock for production, thus carrying energy security benefits for a hydrogen economy.

However, questions and challenges for both the U.S. and Texas Gulf Coast remain: Why hasn't the Texas region become a hydrogen hub organically, given that it is home to an already-active hydrogen industry? What defines a hydrogen hub, and what services do hubs provide? What are the requirements for a successful and functional hydrogen hub? What is the current state of the U.S. and Texas hydrogen markets? What are the challenges and missing elements in the regulatory framework at both the national and state levels that need to be addressed to drive the development of a hydrogen hub on the Texas Gulf Coast? Lastly, what policies are required to ensure a successful, functioning hydrogen hub in Texas?

In fall 2021, the Center for Energy Studies (CES) at Rice University's Baker Institute for Public Policy began convening a stakeholder working group to discuss prerequisites for the significant expansion of hydrogen production and use in the Texas Gulf Coast region. Comprising representatives from industry, nongovernmental organizations, and academia, the working group's central aims were to:

- Identify the current and future scale of the potential hydrogen market in the Texas Gulf Coast region and how the expansion of hydrogen could benefit regional decarbonization efforts.
- Identify the economic, legal, regulatory, and infrastructure barriers for deploying the capital and technology required to scale up a hydrogen market; regarding legal

and regulatory barriers, specifically, it will be important to develop a plan to identify and address specific issues that could hinder or accelerate potential hydrogen projects.

- Engage with policymakers and regulators at the local, state, and national levels about the working group's findings and recommendations and receive feedback; this is a vital part of the general discussions on regulatory and legal issues, capital deployment, and potential project sites.

The working group's efforts are complementary to other ongoing projects, including The University of Texas at Austin and GTI Energy's H2@Scale in Texas and Beyond initiative and Center for Houston's Future's work to evaluate commercial prospects for a regional hydrogen hub. These projects aim to evaluate the deployment costs and feasibility of different hydrogen technologies and associated infrastructure. By contrast, our focus is on the economic, legal, regulatory, and infrastructure impediments to the expansion of a hydrogen market; we do not aim to assess any specific infrastructure pathways nor do we aim to evaluate the feasibility of specific hydrogen production and use technologies. In fact, our effort is agnostic to specific hydrogen technologies, the breadth of which is illustrated by the so-called hydrogen rainbow. Rather, we focus on the prerequisites for expanding the hydrogen market.

We begin this paper by explaining the impetus for considering hydrogen in the broader energy landscape. Next, we highlight the diversity of hydrogen production technologies, followed by a review of the ongoing efforts around the world to develop national hydrogen strategies. We then discuss the results of a survey of Baker Institute Hydrogen Working Group participants. Because the culmination of the literature review and survey highlights the importance of hubs for the expansion of hydrogen production and use, we next discuss hubs and hub services.

In the following sections, we discuss the U.S. natural gas market as a case study for what could transpire with hydrogen. Specifically, we consider the historical unbundling of the natural gas pipeline market in the 1990s, its effects on natural gas pipeline operators, liquidity and trading of natural gas, natural gas market development, and how the hydrogen industry could emulate a path already trodden to achieve market growth. We then examine the current state of play for hydrogen at the national level and in the state of Texas. At the state level, we also assess relevant provisions in state legislation and the policy incentives currently in place to promote hydrogen deployment. Finally, we discuss policy recommendations to support the growth of the hydrogen market on the Texas Gulf Coast.

II. The Energy Transition as Motivation for Hydrogen Expansion

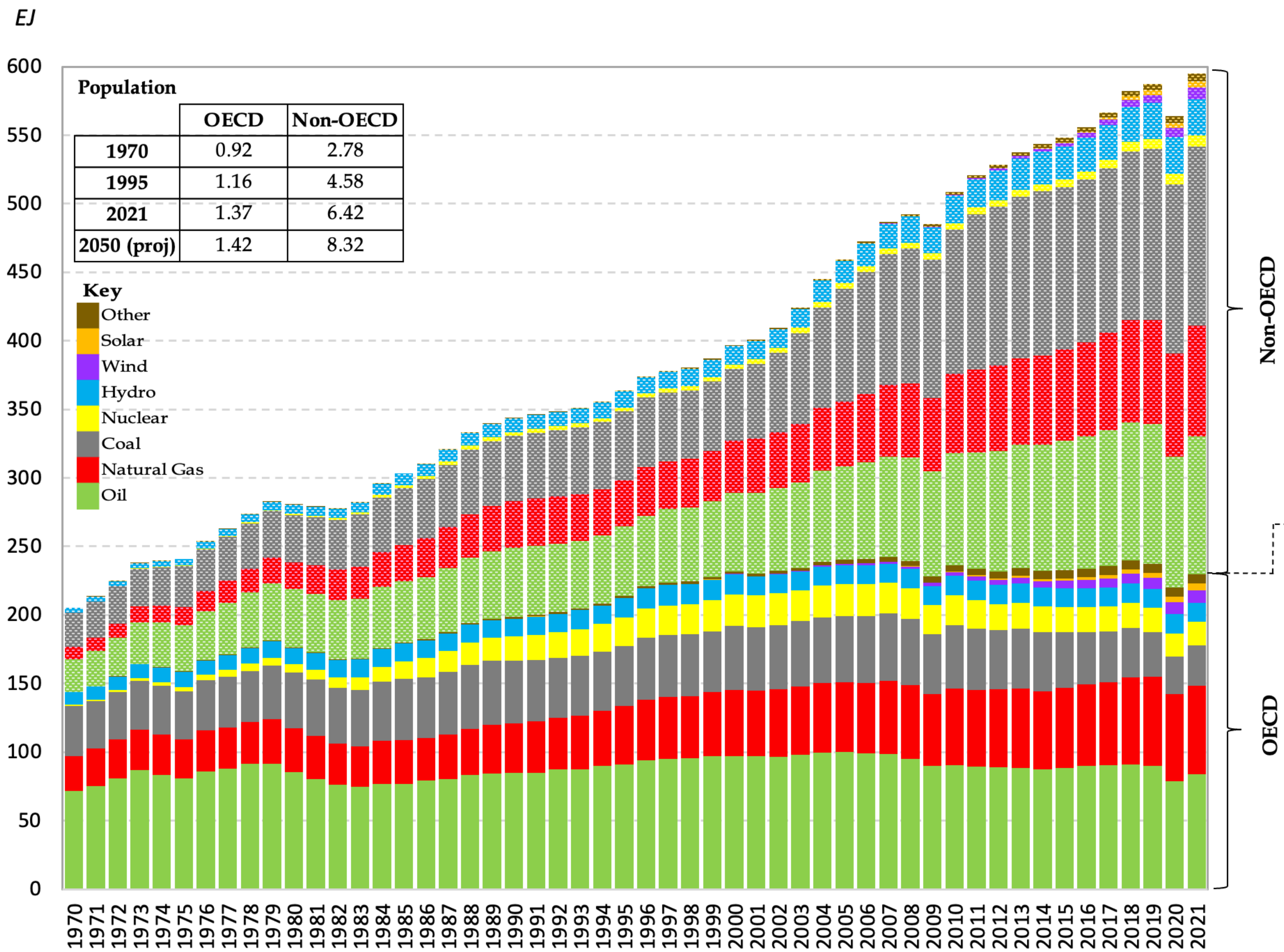
The global energy industry is undergoing dramatic change. Technological change, shifting environmental preferences, the ever-present role of geopolitics in energy trade and access, and energy security concerns — interlaced with national welfare and economic growth priorities — all dominate the current discourse on energy transitions.

The reduction of energy's carbon footprint is a driving force in energy transitions — one that is not without its challenges. Certainly, costs are declining for a number of new energy technologies, and this holds much-touted promise for delivering low-cost, low-carbon energy solutions. However, it is important to remember that the cost of *generating* a unit of energy is not the same as the cost of *delivering* a unit of energy. This is not a trivial statement; in fact, it is at the core of understanding how future energy systems will evolve.
Over the past decade, innovations in technology and processes unlocked unconventional oil and natural gas resources in the U.S., making the U.S. oil and gas industry the fastest-growing in the world and radically shifting the global energy paradigm. At the same time, strong economic growth in China, India, and other developing nations has been the harbinger of significant energy demand growth, with profound implications for energy trade. Indeed, the center of gravity in the world of energy has shifted toward Asia and away from the U.S. and Europe, representing a dramatic change from the previous 100-plus years.

On the global scale, the share of oil, natural gas, and coal collectively constituted 82.3% of global energy demand in 2021, compared to 85.6% in 1995 and 93.3% in 1970. Despite the decline in share, demand for the fuels increased by 62.6% from 1970 to 1995 and by another 57.2% to 2021 (see Figure 1). This speaks to the continued expansion of the global energy system to accommodate economic growth and explains why global CO_2 emissions continue to climb despite pledges by many nations to transition away from fossil fuels. Commitments at the national, regional, municipal, and company levels to achieve net-zero CO_2 emissions have multiplied rapidly. At the national level, policy is evolving to support a portfolio of solutions. At the company level, this is manifest in different decarbonization strategies that tend to reflect the aspirations of investors, current policy support for different pathways, and the company's comparative advantages. Ultimately, innovation must engender a sufficient return on investment in order to attract capital and drive sustainable transitions.

The future is uncertain, but, as has always been the case, economic growth and innovation will dictate how energy markets transition, as well as the pace of change that emerges. Over the past several years, environmental policy and technological innovation have propelled wind and solar energy growth in the U.S. and Europe. Coupled with a significant increase in natural gas use, this has resulted in falling coal consumption in those regions. This has led to a decline in CO_2 emissions in the U.S. and Europe, although the scale of energy systems and the legacy of infrastructures that characterize them mean that fossil energy resources will remain an important part of the energy mix for some time — especially when taking energy security concerns into consideration. Accordingly, the portfolio of options to decarbonize energy use is growing, highlighted by efforts to deploy carbon capture (both engineered and nature-based) and hydrogen technologies to achieve long-term decarbonization goals.

Figure 1. Global Energy Use by Primary Source, OECD and Non-OECD, 1970-2021



Non-OECD

	1970	1995	2021
Other	0.05	0.57	5.66
	0.1%	*0.4%*	*1.6%*
Solar	0.00	0.00	4.80
	0.0%	*0.0%*	*1.3%*
Wind	0.00	0.01	8.34
	0.0%	*0.0%*	*2.3%*
Hydro	3.33	12.05	26.69
	5.4%	*8.0%*	*7.3%*
Nuclear	0.06	2.71	8.04
	0.1%	*1.8%*	*2.2%*
Coal	24.93	49.94	130.41
	40.8%	*33.4%*	*35.7%*
Natural Gas	8.96	33.61	80.73
	14.7%	*22.5%*	*22.1%*
Oil	23.76	50.79	100.59
	38.9%	*33.9%*	*27.5%*
Total	61.08	149.68	365.26

OECD

	1970	1995	2021
Other	0.28	1.51	6.98
	0.2%	*0.7%*	*3.0%*
Solar	0.00	0.01	4.93
	0.0%	*0.0%*	*2.1%*
Wind	0.00	0.08	9.20
	0.0%	*0.0%*	*4.0%*
Hydro	9.18	14.39	13.57
	6.4%	*6.7%*	*5.9%*
Nuclear	0.75	21.02	17.27
	0.5%	*9.8%*	*7.5%*
Coal	36.48	43.52	29.69
	25.3%	*20.3%*	*12.9%*
Natural Gas	25.66	42.37	64.62
	17.8%	*19.8%*	*28.1%*
Oil	71.66	91.20	83.62
	49.8%	*42.6%*	*36.4%*
Total	144.00	214.10	229.89

Source: Energy data for figure are from *BP Statistical Review of World Energy*, 2022. Population data are from United Nations.

Alongside government policies that are being designed with a specific goal of reducing CO_2 emissions and facilitating energy transitions, shifts in investor and consumer sentiment are motivating an emphasis by firms on reducing net CO_2 emissions. In fact, a preference for improved sustainability in operations is driving environmental, social, and governance (ESG) initiatives within companies across the energy landscape. In turn, many companies have issued net-zero CO_2 emission decrees and have begun to publish sustainability reports annually. In doing so, they are bringing a relatively new degree of transparency to their operations, with some even reporting scope 1 emissions (those resulting directly from business operations) and scope 2 emissions (those resulting indirectly from business operations, such as emissions associated with the production of energy purchased by a firm). Some are also attempting to quantify scope 3 emissions, which are those that occur in the value chain of a firm's activities that are not included in scope 2 calculations. In sum, companies are responding to investor pressures to produce energy with a lower environmental footprint and are taking steps to demonstrate their environmental performance.

In the developing world, led by China and India, growth in renewable energy sources has been accompanied by significant increases in the use of coal, oil, and natural gas. This underscores the "all of the above" energy strategy deployed in those countries to fuel economic growth. In fact, energy use outside of the Organisation for Economic Cooperation and Development (OECD) member countries surpassed energy use in the OECD in 2007 and continues to rise. As the majority of the world's population (over 6.4 billion in countries not part of the OECD) seeks and attains greater standards of living, the global energy system will continue to evolve and expand in profound ways, with implications for trade, geopolitics, energy prices, and welfare.

China has already captured a dominant global role in the supply chains for solar power, batteries, and key wind turbine components, as well as the upstream production and processing of the minerals and metals that feed those supply chains. This has driven geopolitical and national security concerns for countries that are pressing to transition their energy sectors toward renewable energy technologies. Concerns related to the war in Ukraine have wreaked havoc on energy markets and energy transition policies across the globe. In fact, in light of the war in Ukraine, energy security concerns have reentered public policy discourse in a way not seen in some time, with impacts for both developed and developing nations. It remains to be seen how all of this will affect energy investment strategies at the global, national, and local levels.

Despite the continued expansion of global energy demand, only about 6.9 billion of the 8.0 billion people on the planet have access to modern energy services, and more than half of the 6.9 billion that do are not availed of *reliable* energy services.[4] As such, it is highly likely that the global energy system will continue to expand to meet the demands of the current global community, not to mention the projected additional 2 billion people who will be born by 2050, most of whom are in the developing world. The sheer scale of this task demands innovative solutions.

Energy is very infrastructure-intensive. Using energy requires massive supply chains that connect production to consumption through a network that involves conversion, transmission, and distribution. As such, there is a massive *legacy* of infrastructure associated with each type of energy used. Ignoring this legacy inevitably leads to problems, since the full cost of adopting new energy technologies includes the cost of deploying the assets that are required to deliver energy services to consumers. In other words, the full cost of any new energy resource is not just the cost of producing the energy; it is also the cost of developing the full supply chain to support its production and manage its delivery into the market.

New technologies that can leverage *existing* supply chains and their associated infrastructures have a distinct advantage, i.e., they can piggyback on the sunk costs of legacy infrastructure. Technologies that require the development of completely new supply chains do not enjoy that luxury, which can render them too costly to adopt, even though they may be low-cost in terms of generating useful energy services. The proverbial "valley of death" is often the final resting place for new energy technologies that ignore the economic hurdles of deployment costs and the sunk costs of legacy assets.[5]

Fossil fuels remain a dominant source of energy globally. There is a large amount of infrastructure in place to support the supply chains that produce, transport, and use fossil fuels. Finding ways to leverage the existing hydrocarbon supply chain could make for an excellent enabler of low-carbon energy outcomes and drive low-cost pathways to decarbonization. Moreover, given the scale of global energy demands for modern economic activity, societies will need to use everything available, and do so sustainably. This is where hydrogen has a real opportunity to be a centerpiece of the low-carbon future of energy. Hydrogen can leverage legacy infrastructures related to the production and transportation of fossil fuels while also affording the potential to develop new non-fossil-fuel-related infrastructures. Texas is ideally situated to serve in this capacity, as it is home to an abundance of energy infrastructure as well as the majority of the nation's existing hydrogen market. Hence, the region already has a hydrogen backbone and central nervous system from which to grow.

III. Hydrogen's Potential Rests in Its Diversity[6]

a. Hydrogen's Many Uses: Now and in the Future

Hydrogen is the simplest and most abundant element on Earth. It already occupies a dominant place in our current energy system, facilitated in combination with a prolific natural hydrogen carrier — carbon — in the form of molecules known generically as hydrocarbons. But the negative CO_2 externality associated with hydrocarbon combustion is driving greater interest in the direct use of hydrogen.

The use of hydrogen as an energy carrier has held intrigue for many years, but technical and commercial challenges have kept it from proliferating. Currently, hydrogen is used in refining to remove sulfur from crude oils, fertilizer production, metallic-ore reduction, and a number of industrial applications in chemicals, textiles, and electronics. Perhaps the most famous use of hydrogen is in liquid form for rocket fuel. Looking to the future, hydrogen has several potential applications that could be significantly expanded across a range of end-use sectors from transportation to electric power to industry. For example, in transportation applications, hydrogen can be used in fuel cells to power passenger and commercial vehicles, heavy-duty trucks, buses, trains, and waterborne vessels.

Beyond transportation, hydrogen can be used in fuel cells to generate electricity for backup power and/or distributed energy applications, and it can be blended into natural gas for use in gas turbines to generate electricity. Hydrogen can also be stored for later use in power generation to manage load variability in power systems, for example when intermittent renewables are not available. For hard-to-decarbonize applications, hydrogen can be used for steel, cement, chemical, and other manufacturing processes not easily electrified.

The fact that hydrogen can be used in so many different applications across multiple sectors makes it prime for playing a substantial role in transitioning energy systems. But demand must be met with supply for such a transition to occur.

b. Hydrogen's Many Colors Are an Advantage for Growth[7]

Hydrogen can be produced in many different ways, providing numerous relatively low-cost options for meeting demand. Indeed, the lowest-cost option for hydrogen production may be different depending on the region. To the extent that this is the case, the principle of comparative advantage will play an important role in shaping how regions adopt hydrogen and what technologies are chosen for production.

The "hydrogen rainbow" is a color-coding of the various processes for producing hydrogen, where each color is associated with a different means of production (see Table 1). There is often criticism levied at the use of color-coding when discussing hydrogen. However, it is useful as a means of highlighting the diversity of production technologies. Once hydrogen is produced and moves into distribution and use, the molecule is agnostic to the production technology. So, as a means of discussing different production technologies, we adopt the convention of referring to the hydrogen rainbow, but, as will be seen below, the colors themselves have little bearing on future market development. Rather, the CO_2 intensity of production is more relevant for production technology deployment, especially when it comes to policy support, but even then, production costs matter. Thus, the availability of low-cost feedstock and electricity, access to distribution infrastructure, and demand growth will ultimately determine the competitiveness of different production technologies.

Currently, "grey" hydrogen is the overwhelmingly dominant means of production. It is primarily derived from natural gas using steam-methane reforming, resulting in CO_2 emissions. But there are a number of other technologies that can be used to produce hydrogen, many of which eliminate CO_2 emissions.

Notably, the suite of technologies used to produce hydrogen includes the use of hydrocarbons as a feedstock along with CO_2-removal technology. "Blue" hydrogen leverages existing production, transportation, and distribution infrastructures for hydrocarbons, but eliminates CO_2 emissions by installing carbon-capture technologies alongside steam reformation. In this way, blue hydrogen has the potential to avoid stranded costs being imposed on existing assets, while also avoiding added fixed costs for new infrastructures that may be needed with other low-CO_2 energy options.

"Turquoise" hydrogen is similar to blue hydrogen in that it can also leverage existing hydrocarbon production, transmission, and distribution infrastructures. But it also introduces a carbon-to-value proposition that can dramatically alter the technology's commercial prospects. For example, material science innovations that use solid carbon as a feedstock for carbon nanotechnologies and advanced carbon-based materials have the potential to replace steel and other materials in construction and vehicle manufacturing. In the case of vehicles, in particular, light-weighting vehicles can improve fuel efficiency and electric vehicle (EV) range, reducing the energy requirement per unit of distance travelled and thus carrying an added carbon-reduction benefit.

Table 1. The Colors of Hydrogen

Grey	Produced from natural gas using steam-methane reforming. The most common form of hydrogen production currently in use. Results in CO_2 emissions.
Brown	Produced from the gasification of fossil fuel feedstock, usually coal. Often discussed as a potential future use of coal. Results in CO_2 emissions.
White	Produced as a byproduct of an industrial process. CO_2 emissions are dependent on the industrial process.
Yellow	Produced by electrolysis using electricity from solar power. No CO_2 emissions depending on the source of power generation. Leverages an existing power grid. Can be carbon-neutral if carbon capture is deployed at the sources of fossil-generated power.
Blue	Grey or brown hydrogen with carbon capture. CO_2 emissions are substantially reduced. Modifies existing production methods, thus leveraging legacy, or existing, infrastructures.
Turquoise	Produced by methane pyrolysis with a solid carbon by-product. CO_2 emissions are substantially reduced. Leverages existing natural gas infrastructures. Opens "carbon-to-value" propositions, as solid carbon can be a replacement for carbon black and used as a feedstock in advanced carbon material applications.
Green	Produced by electrolysis using electricity from renewables. No CO_2 emissions.
Pink	Produced by electrolysis using nuclear power. No CO_2 emissions.

Source: This table is derived from a report by the North American Council for Freight Efficiency, (https://nacfe.org/emerging-technology/electric-trucks-2/making-sense-of-heavy-duty-hydrogen-fuel-cell-tractors/). There are multiple derivatives of the color palette for hydrogen technologies. For example, yellow is sometimes associated with solar power, brown with lignite, and black with coal.

Production technologies that utilize electrolysis to split hydrogen from water ("yellow," "green," and "pink" hydrogen) generate no CO_2 at the point of conversion. Moreover, the hydrogen that they produce is indistinguishable from other hydrogen forms. Much emphasis has been placed on electrolysis for hydrogen production, with a majority of attention given to green hydrogen to date. This stems directly from the fact that when paired with rapidly expanding renewable sources of electricity, electrolyzers can produce a CO_2-free source of hydrogen.

The multitude of hydrogen production technologies have the potential to support a more rapid evolution and scale-up of the market, since the technologies all produce the same commodity — hydrogen — but likely differ in relative cost in different parts of the world. Green hydrogen costs are likely to be lower in regions with an abundance of wind and/or solar resources, just as blue and turquoise hydrogen costs are likely to be lower in regions with abundant natural gas resources and legacy natural gas infrastructure. Altogether, the variety of hydrogen production technologies support regional arbitrage opportunities that can promote competition, liquidity, and trade.

c. Other Considerations

Hydrogen's versatility lies along its entire value chain. It can be produced in many ways, each with a different carbon footprint. According to Energy Web Atlas, over 97% of the hydrogen currently produced in the United States (from 120 plants) is grey hydrogen.[8] But with appropriate incentives or cost-recovery mechanisms, the CO_2 emissions can be captured and stored without damaging commercial value, turning the grey hydrogen blue. While various production methods are favored due to their lower CO_2 emissions, concerns have been raised regarding hydrogen itself acting as an indirect greenhouse gas (GHG).[9] This begets concerns related to hydrogen leakage along the supply chain. Notably, the potential impact of hydrogen on low-carbon energy transition goals depends on its GHG impact; as such, it is important to evaluate hydrogen's impact at the system level across the entire supply chain. Given current funding and regulatory guidance in the U.S., this includes both social and economic dimensions, as well as the environmental footprint of the production technology. Some literature has indicated that, compared to grey hydrogen, hydrogen produced via electrolysis with wind power and/or gasification with biomass currently underperforms in certain social and economic dimensions, despite its environmental advantages.[10]

Assuming various environmental concerns can be adequately addressed, hydrogen's diverse application pathways have significant potential for decarbonizing the economy. But expansion beyond traditional industrial applications will require significant investment in infrastructure and well-designed market structures with appropriate regulatory architecture. Currently, California is the only state in the U.S. that operates a decently sized network of hydrogen refueling stations for fuel cell vehicles (FCEVs).[11] However, even in California, FCEV market penetration is very small, especially when compared with EV adoption rates. Notably, EVs do not require a similar level of refueling infrastructure as a prerequisite for consumer adoption, since electricity delivery is already widespread to households, commercial establishments, and elsewhere. This means that for EVs, recharging capabilities can be expanded at a relatively low cost, at least up to the point where the existing grid can handle the load. FCEVs, on the other hand, require investment in refueling capability from the start, which represents a fixed-cost barrier to adoption.

IV. A Rapidly Evolving Hydrogen Discourse: A Brief Literature Review

There is a large, emerging body of literature that seeks to quantify the potential of hydrogen and identify end-uses, key enablers, and barriers to a hydrogen economy. Much of this work is in the form of "roadmaps" and case studies. Among the points of emphasis that often emerge is an identification of hydrogen "hubs" as critical for the scale-up of hydrogen beyond its current footprint, especially if it is to become a significant part of a low-carbon energy supply portfolio.

At the global level, the Hydrogen Council and McKinsey & Company examined hydrogen markets and cost-competitiveness in a 2021 report.[12] The report recognized a burgeoning set of hydrogen applications in international seaborne transport, including liquid hydrogen, liquid organic hydrogen carriers, and ammonia. Interestingly, the report noted that green ammonia would be a cost-competitive option in maritime applications by 2030. Regarding hydrogen market expansion, the report identified co-locating supply with demand as the most competitive approach in the short term. This implies "cluster" development with large-scale off-takers in port areas, industrial complexes, and export locations. To that end, the report stressed the importance of accessible and shared infrastructure in ensuring the success of hydrogen hubs.

Similarly, a report by the Energy Transitions Commission[13] pointed to developing hydrogen clusters as a necessary action for the fuel's scale-up. It proposed cluster archetypes centered on ports, cities, refining centers, fertilizer production centers, and steel plant sites. Other requirements identified for a hydrogen economy included infrastructure for hydrogen transport and storage, the expansion of carbon capture and sequestration activities, policies to support and encourage demand growth, unimpeded supply chain development, a delineation of safety and quality standards, social acceptance, and a clean hydrogen certification scheme. The study also quantified the carbon pricing required to accelerate low-carbon hydrogen, estimating that a carbon price of $50-$70 per ton would make blue hydrogen with 90% carbon capture cost-competitive against grey hydrogen. The report also noted that even with a hydrogen production cost of $1/kg, explicit carbon taxes or implicit carbon pricing would be required to overcome fixed-cost hurdles and incentivize market growth.

In another report, consultancy DNV forecast that blue hydrogen would remain dominant over green hydrogen through 2030.[14] The publication surveyed over 1,000 energy professionals on their opinions on the outlook for a hydrogen economy. DNV found that profitability, sustainability, and decarbonization requirements were the top drivers for industry involvement in hydrogen. The most significant risks identified were high production costs, missing or changing regulatory frameworks, and lack of investment in supportive infrastructure. Similarly, the most significant barriers included the lack of infrastructure, technical expertise, and market entry opportunities. On the other hand, the most critical enablers included cost reductions in hydrogen production technologies and national hydrogen strategies that identify and adopt supportive policies. In fact, the DNV report highlighted three key areas where policy can act to accelerate hydrogen — profitability, regulation, and infrastructure — and identified action items such as establishing a hydrogen-inclusive regulatory framework, enhancing profitability with fiscal incentives and market signals such as CO_2 pricing, and reducing market barriers by making infrastructure more accessible.

In a 2020 report, the Fuel Cell & Hydrogen Energy Association (FCHEA) laid out a four-phase roadmap toward a U.S. hydrogen economy between 2020 and 2050.[15] The study saw hydrogen capable of supporting 14% of U.S. energy requirements by 2050, with production between 20 million tonnes per annum (MTPA) and 63 MTPA. The report recognized light- and heavy-duty transport, residential and commercial heating, and distributed power generation as having significant long-term (to 2050) demand potential. It also highlighted the use of hydrogen as a balancing fuel for power generation with intermittent renewables to supply reliable power to microgrids, with an emphasis on high-risk communities, as an emerging application.

In 2022, the Great Plains Institute examined the decarbonization potential of hydrogen production and use in tandem with CCUS for the United States.[16] The study identified the Permian Basin in West Texas and eastern New Mexico, Arkansas and Oklahoma, and the Gulf Coast as three of 14 potential “carbon and hydrogen hubs” that would focus on co-locating CCUS and hydrogen opportunities. The study estimated a potential 1.4 billion metric million British thermal unit (MMBtu) fossil fuel displacement opportunity in the Gulf Coast-Houston region. In particular, 57 facilities in the region are eligible to leverage the existing 45Q tax credit for CCUS, in addition to incentives for hydrogen investment and production.

The discussion of hydrogen hubs has emerged as central to the future of hydrogen markets. Indeed, as Table 2 indicates, a multitude of studies, analyses, and agreements have identified hub formation as a necessary condition for hydrogen market development and growth. To be clear, Table 2 is not exhaustive, but it highlights the extent to which hubs are a centerpiece of efforts internationally. In the U.S., for example, there are numerous studies focused on regional hydrogen opportunities. Many are aimed at the DOE’s $8 billion “Hydrogen Shot” initiative for hydrogen hub development, so there is broad alignment on the hub concept, with each study making a case for specific regions using the IIJA as the point of reference.

Table 2. Select Regional Hydrogen Efforts

United States	Hydrogen and Fuel Cell Technologies Office | Department of Energy; DOE Update on Hydrogen Shot, RFI Results, and Summary of Hydrogen Provisions in the Bipartisan Infrastructure Law: Text Version | Department of Energy
• Based around provision of the IIJA, which: ○ Defines a "regional clean hydrogen hub" as "a network of clean hydrogen producers, potential clean hydrogen consumers, and the connective infrastructure located in close proximity." ○ Provides $8 billion for at least four regional clean hydrogen hubs for 2022-2026 with a production standard (2 kg CO_2/kg H_2). ○ Stipulates that "to the maximum extent practicable, each regional clean hydrogen hub shall be located in a different region of the United States and shall use energy resources that are abundant in that region." ○ Requires that all components of the value chain (production, processing, delivery, storage, and end-use) be clean. ○ Requires hub selection based on diversity in feedstock, end-use, and geography, with priority to natural gas and employment.	
Canada	Hydrogen Strategy for Canada (nrcan.gc.ca)
• Conceptualizes "deployment hubs" that bring supply, demand, and key players together to "develop and implement regional plans that build on specific strengths and opportunities while identifying unique barriers and challenges." Aims to: ○ Develop regional deployment hubs to demonstrate, validate, and implement business cases across the full value chain. ○ Implement multi-year funding programs. ○ Establish a long-term regulatory environment. ○ Create co-funding opportunities with the private sector and multiple levels of government.	
Edmonton, Canada	Why Hydrogen | Edmonton Region Hydrogen HUB (erh2.ca)
• Describes hydrogen hubs as "initiatives designed to accelerate the development of regional hydrogen economies in locations across the country with low-cost, low-carbon hydrogen" that "will later be connected to others across the country to break the vicious cycle of insufficient hydrogen supply and demand, and achieve sufficient scale for a strong Canada-wide hydrogen economy." • Alliance of governments, First Nations, academia, and economic development leaders. • Comprises 25-plus projects along the value chain (specific projects are unclear).	
Australia	Growing Australia's hydrogen industry - DCCEEW; Activating a Regional Hydrogen Industry – Clean Hydrogen Industrial Hubs: Hub Development and Design Grants | business.gov.au
• Defines "hub" as "a region that has the potential to aggregate demand for hydrogen" or a region "where various users of hydrogen across industrial, transport and energy markets are co-located"; notes that "These hubs could be coastal industrial clusters or co-located near ports. The creation of hubs is expected to be an effective springboard to growing a hydrogen economy." • Calls for sufficient supply chains for up to seven prospective at-scale hubs by 2025 via the Australian Clean Hydrogen program. • Hub Development and Design Grants (AU$23 million allocated) and Hub Implementation Grants (AU$430 million allocated) through the Industrial Hubs Program.	
Japan	20221202004-1.pdf (meti.go.jp); Industry-academia-government collaboration in Yamanashi Prefecture aiming to create 'Yamanashi Hydrogen and Fuel Cell Valley' | Stories | Science Japan (jst.go.jp)
• Aims to strengthen rules around hydrogen market development and regulation, as stated through a memorandum of cooperation with the European Commission. • Promotes research and development through the Yamanashi Hydrogen and Fuel Cell Cluster, a hydrogen and fuel cells-related industry association.	

<table>
<tr><td>Scotland</td><td>Hydrogen action plan: draft - gov.scot (www.gov.scot)</td></tr>
<tr><td colspan="2">
• Conceptualizes “regional hydrogen hubs that combine production, storage and distribution with multiple end-use applications.”
• A regional hydrogen energy hub is defined as “a geographic location (region, city, island, industrial cluster) that is host to the entire hydrogen value chain, from production, storage, and distribution to end-use” and that “will include multiple end-users with applications ideally covering more than one sector.” In addition, “this aggregation of cross-sectoral demand and co-location of the whole-hydrogen value chain minimizes the cost of essential supporting infrastructure and makes the hub model an efficient pathway to producing hydrogen at scale and increasing demand.”
• Led by industry and the private sector with strategic support through an Emerging Energy Technologies Fund (EETF).
</td></tr>
<tr><td>The North Sea Region (HyTrEc)</td><td>acc-hydrogen-hub-business-case.pdf (northsearegion.eu)</td></tr>
<tr><td colspan="2">
• Aims to develop a “Hydrogen Supply Hub which will provide low cost, low carbon hydrogen to the buses [in Aberdeen, Scotland] and other emerging hydrogen applications over the next decade.”
• Provides over 15 million pounds from the Scottish government’s Energy Transition Fund to support the establishment of the Aberdeen Hydrogen Hub.
• Focuses on light- to medium-duty transport applications, especially buses, using the supply of green hydrogen as a starting point.
• Engages joint ventures or consortia with investment and delivery partners.
• Involves two phases of expansion: 1) development of supply infrastructure (2020-2023) and 2) expansion of electrolyzer capacity to at least 8 megawatts, requiring at least three refueling locations (2023-2032).
</td></tr>
<tr><td>HyNet North West (United Kingdom)</td><td>HyNet_NW-Vision-Document-2020_FINAL.pdf</td></tr>
<tr><td colspan="2">
• Aims for its hydrogen network to “produce, store and distribute hydrogen to decarbonise the North West of England and North Wales” alongside its carbon capture and storage initiative.
• Will complete its first operation by 2025.
• Has run fuel-switching demonstration projects.
• Conducted front-end engineering design study for the hydrogen supply at Stanlow Refinery in England.
• Tested injection of a hydrogen blend into a closed gas grid.
• Has carried out technical studies for hydrogen as a fuel for heavy-duty vehicles.
• Collaborates with the national government on natural gas-to-hydrogen pipeline conversion.
</td></tr>
<tr><td>France</td><td>DP - Stratégie nationale pour le développement de l'hydrogène décarboné en France.pdf (ecologie.gouv.fr)</td></tr>
<tr><td colspan="2">
• Issued a call for “territorial hydrogen hub” project proposals; the projects will promote large-scale ecosystems supporting a variety of hydrogen uses, including industry and mobility, to maximize economies of scale. The call for projects will be endowed with 275 million euros by 2023.
</td></tr>
<tr><td>Hungary</td><td>a2b2b7ed5179b17694659b8f050ba9648e75a0bf.pdf (kormany.hu)</td></tr>
<tr><td colspan="2">
• Describes hydrogen valleys and clusters, which “act as a demonstration of an entire hydrogen ecosystem in a region, as a portfolio of interconnected projects.”
• Aims to establish two hydrogen valleys in Hungary by 2030 to promote the development of interconnected hydrogen-value-chain networks within certain geographical regions; one of six prioritized projects in the strategy with an estimated funding of 10-15 HUF bn.
</td></tr>
<tr><td>Norway</td><td>The Norwegian Government’s hydrogen strategy - Towards a low emission society (regjeringen.no)</td></tr>
<tr><td colspan="2">
• Will “establish a functional and commercially sustainable value chain for hydrogen in the north of Western Norway,” the aim of which is to “develop and demonstrate a complete supply chain for green hydrogen” in the town of Geiranger.
</td></tr>
</table>

The Netherlands	Government Strategy on Hydrogen | Publication | Government.nl
• Supports local pilot demonstration projects via the Energy Innovation Demonstration Scheme (DEI+). • Calls for investment in infrastructure along the entire hydrogen value chain. • Supports hydrogen studies and business case development. • Calls for policy to promote international partnerships, regional cooperation, and energy strategy identification, research, and innovation. • Calls for the implementation of relevant laws and regulations and reviews the use of the existing natural gas grid. • Developing an origin guarantee certification system.	
Rotterdam, Netherlands	Hydrogen in Rotterdam | Port of Rotterdam
• Calls for a large-scale hydrogen network across the Rotterdam port complex in order to make "Rotterdam an international hub for hydrogen production, import, application and transport to other countries in Northwest Europe." • Projects include an industrial conversion park, including Shell's electrolyzer plant proposal; an open-access hydrogen pipeline that will form the backbone of the port's hydrogen infrastructure; 2-gigawatt offshore wind connections; blue hydrogen production with carbon storage in depleted gas fields; and import terminals and pipelines to establish a climate-neutral transport corridor.	
Germany	hydrogen-strategy-for-north-germany.pdf (hamburg.de)
• Notes that "the generation, temporary storage, distribution and use of hydrogen are geographically concentrated" and "serve as starting points for establishing a hydrogen economy in North Germany." • Describes hydrogen hubs as "locations that feature a critical mass of demand for hydrogen in geographic proximity to hydrogen production facilities and hydrogen infrastructure (storage, transport). The generation and distribution (provision), as well as use (e.g., in mobility or industry) are pooled by the hydrogen hub." • Aims to establish the first sets of hydrogen hubs, which are intended for industrial-scale uses, by 2025. • Includes hydrogen readiness research. • Calls for promotion through public relations work. • Develops a catalogue of selection criteria for hub locations. • Identifies suitable locations by the criteria. • Includes contacting potential partners along the value chain and encouraging investors with regard to hub creation.	
European Union	EUR-Lex – 52020DC0301 – EN – EUR-Lex (europa.eu)
• Uses the concept of a "hydrogen valley," defined as "a geographical area — a city, a region, an island or an industrial cluster — where several hydrogen applications are combined together into an integrated hydrogen ecosystem that consumes a significant amount of hydrogen, improving the economics behind the project. It should ideally cover the entire hydrogen value chain: production, storage, distribution and final use." • Calls for "local production of hydrogen based on decentralised renewable energy production and local demand, transported over short distances. In such cases, a dedicated hydrogen infrastructure can use hydrogen not only for industrial and transport applications, and electricity balancing, but also for the provision of heat for residential and commercial buildings." • Aims to stimulate investment and establish a hydrogen fueling network. • Outlines the need for an EU-wide hydrogen logistical infrastructure.	

Sources: Authors compiled from sources noted in table.

V. Baker Institute Working Group Reflections on Hydrogen

In April 2022, the CES surveyed the Baker Institute Hydrogen Working Group regarding the future of hydrogen, its potential for growth, and relevant legislative priorities. We asked respondents to self-identify their involvement in the hydrogen value chain while keeping the responses anonymous. Their involvement ranges across a number of points in the hydrogen value chain — i.e., primary energy source feedstocks, hydrogen production, transport and delivery, storage, conversion to hydrogen-based products, various end-use applications, strategy consulting, academic research, and policy. Table 3 indicates the questions included in the survey.

Table 3. Survey Questions

	Question	Choices (if applicable)
1.	Rank the following hydrogen applications in order of (1) near-term (2030) and (2) long-term (2050) potential for large-scale adoption	**a.** Transportation fuel in heavy-duty applications (trucking, shipping) **b.** Transportation fuel in light duty applications (personal transport, fleet applications) **c.** Energy storage **d.** Electricity generation and balancing services **e.** Industrial fuel **f.** Existing feedstock applications **g.** New feedstock applications (ammonia, syn fuels, etc.) **h.** International trade in hydrogen/hydrogen derivatives **i.** Residential and commercial applications **j.** Other (please specify)
2.	Rank the following drivers in technological, regulatory, and market environment in order of importance for significant expansion of hydrogen activities	**a.** Rapid development of carbon capture and sequestration **b.** Advances in the development of carbon-to-value pathways **c.** Accelerated deployment of renewable generation technologies **d.** Large-scale hydrogen storage capabilities **e.** Federal investment and/or incentives focused on hydrogen technology **f.** Permitting and siting of infrastructure for connecting hydrogen production, storage, and use **g.** Clarity on regulatory jurisdiction along different parts of the hydrogen value chain **h.** Open access requirements on hydrogen pipeline infrastructure **i.** Liquidity in hydrogen markets **j.** Other (please specify)
3.	Rank the following actions policymakers could engage in order of importance for significant expansion of hydrogen activities	**a.** Designate certain regions as “hydrogen hubs” **b.** Expand public-private partnerships for pilot technology demonstrations **c.** Harmonize hydrogen safety standards and codes from production to end-use **d.** Incentivize/require firm electricity sales for intermittent resources (through storage or dispatchable balancing services) **e.** Implement a low carbon fuel standard, or something similar **f.** Streamline permitting and siting for hydrogen infrastructure **g.** Designate sustained fiscal support (such as production tax credits) for low-carbon/zero-carbon technologies **h.** Introduce regulations requiring open access to hydrogen infrastructure **i.** Expand and extend the 45Q tax credit for carbon capture **j.** Other (please specify)
4.	In your own words, define “hydrogen hub”	

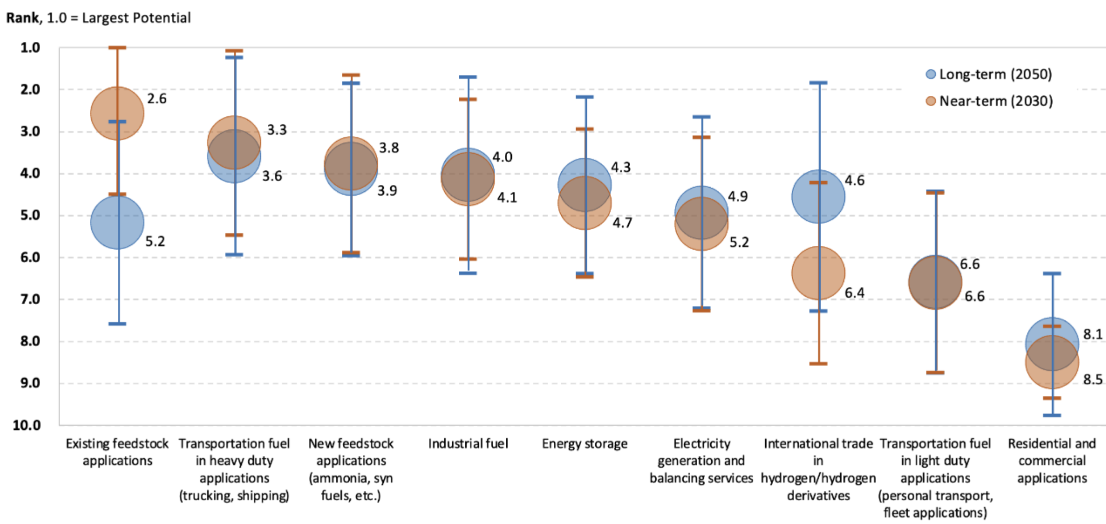
Source: Authors.

Figures 2 through 4 illustrate the survey results. Average rankings and ranges are displayed for Questions 1, 2, and 3. All responses are shown for Question 4.

Survey responses indicated that the timelines for the development of hydrogen opportunities have significant bearing on the perspectives for hydrogen growth. Opportunities that can leverage existing infrastructures and supply chains are deemed as having the greatest near-term prospects for growth, but the opportunities shift to more greenfield options in the longer term. Although not specifically addressed in the survey, working group discussions indicated this shift based on temporality is driven by a general view that markets will deepen in the longer term and afford opportunities for new end-uses of hydrogen, particularly in transportation applications.

As indicated in Figure 2 for Question 1, existing feedstock applications were generally ranked as having the highest potential for growth and development by 2030. This ranking fell to the middle of the pack with regard to long-term growth potential (through 2050). The ability to leverage existing infrastructure makes transitioning existing industrial activities to hydrogen lower-hanging fruit than expanding into new greenfield activities, where fixed costs can be high.

Figure 2. Survey Responses to Question 1 (Average and One Standard Deviation)



Source: Authors.

Across both time frames, respondents saw residential and commercial applications as having the least potential for large-scale adoption. Working group deliberations indicated that if hydrogen uptake in these sectors enters wide-scale adoption, it will likely not be until well into the future, given the substantial fixed costs associated with integrating hydrogen into existing natural gas transmission and distribution networks and appliances.

Interestingly, heavy-duty transport applications were ranked second in both short- and long-term time horizons, while light-duty transport applications were consistently ranked second to last. In accordance with working group discussions, the views on transportation uptake of hydrogen reflected logistical considerations, range, and deployment costs. For example, heavy-duty transportation for moving freight in and out of ports and to and from warehouses and distribution centers involves routes that are relatively fixed, meaning refueling infrastructure can be planned along these routes to capture economies of scale. Moreover, co-location at ports is a leverage point when industrial activities in and around ports are also transitioning to hydrogen.

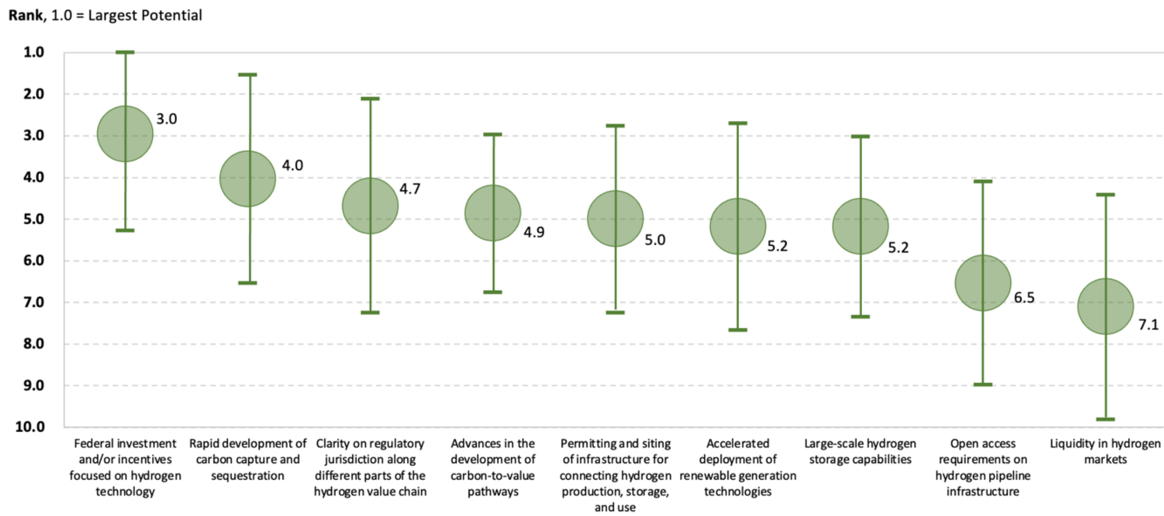
One issue raised in working group deliberations was the misalignment between existing policies and the expanded use of hydrogen in the transportation sector. Policy has been tilted toward encouraging light-duty EVs, which, all else being equal, will discourage light-duty hydrogen vehicles. In states such as California, the existence of a low-carbon fuel standard (LCFS) changes the equation somewhat, but not a lot, as evidenced by the rapid growth of EVs. Such encumbrances do not exist for heavy-duty transport, where plans such as the Environmental Protection Agency (EPA)'s Clean Trucks Program[17] can be a facilitator of change at the margin.

International trade opportunities were ranked fairly low through 2030, reflecting the working group's discussion on the need for significant infrastructure build-out, but the ranking climbed significantly when respondents were asked about longer-term potential. This also reflects the working group dialogue, which indicated that the potential for international trade in hydrogen and hydrogen derivatives is contingent on prior growth in local-use applications. So, in areas where hydrogen use in industrial activities expands, realizing economies of scale in production could yield long-term opportunities for export.

As indicated in Figure 3 regarding Question 2, the average rankings of the nine potential *drivers* for hydrogen expansion are relatively close to each other, but there was substantial variation in the rankings for each question. In fact, seven of the nine choices were ranked as the most important factor by at least one of the respondents. This suggests that a) there are mixed sentiments regarding legislative priorities by the respondents, which reflects, to some extent, respondents' positions in the value chain, and b) that effective hydrogen expansion will require a multipronged approach.

Federal investment and/or incentives focused on hydrogen technology were considered the most important drivers. This reflects a broad agreement in working group discussions that clear and tangible government support would be a powerful enabler of hydrogen market growth. Interestingly, the next two ranked choices (in terms of average ranking) were rapid development of CCUS, followed by clarity on regulatory jurisdiction along the hydrogen value chain. So, the top three choices are squarely in the jurisdiction of policymakers and regulators, but only the top two have seen solid movement as of the time of this writing. Any lack of clarity on regulatory jurisdiction could present a roadblock to significant infrastructure build-out and market growth, despite direct government subsidy support for both hydrogen and CCUS.

Figure 3. Survey Responses to Question 2 (Average and One Standard Deviation)



Source: Authors.

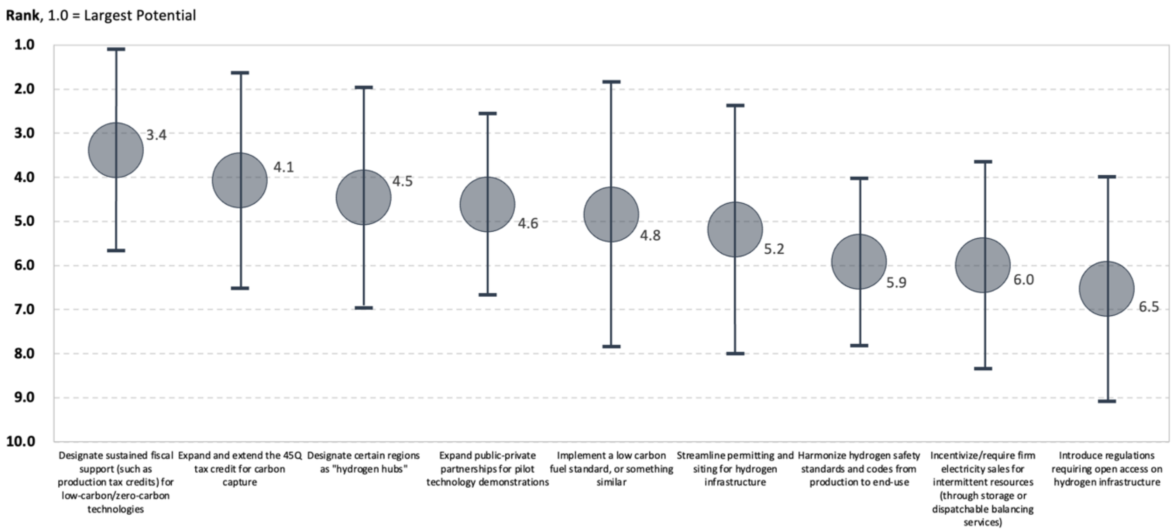
Advances in the development of carbon-to-value pathways were identified as an important driver for hydrogen market growth. In working group discussions, this was not an initial point of emphasis, but it was pointed out that advances in applications that utilize carbon in advanced chemistry or advanced materials applications could be game-changing. If there is a value proposition associated with carbon as a feedstock, then fossil fuel-based hydrogen production technologies that are paired with carbon capture would be able to sell both hydrogen and carbon. Such an outcome would radically alter the commercial valuation of these technologies and could even render subsidy support unnecessary. It was generally acknowledged, however, that the prospect of this occurring in the near term is low, given the technological advances and capital commitments that would be required.

Permitting issues were ranked next, but no respondent ranked them as a top priority. This was revealed in the working group discussions to be a crucial issue. Given recent action by the federal government around incentives (hydrogen hub funding and tax credits), it may become a greater priority as projects are conceived and efforts around securing project financing begin in earnest. Permitting reform is a contentious but high-priority issue at the federal level. When coupled with clarity on regulatory jurisdiction, we see a set of emerging priorities for policymakers to address when it comes to hydrogen market growth.

Renewable generation technology and hydrogen storage were the next two in line; both are infrastructure-related priorities and are important for new supply and supply-chain management, respectively, in the hydrogen market. They also both connect to permitting issues. Surprisingly, drivers that encourage trade, including open access to hydrogen pipelines and liquidity in hydrogen markets, were ranked the least important. This was surprising because factors impeding access to infrastructure can present a barrier to market entry and inhibit market development. In fact, there were some very active discussions in the working group meetings regarding the importance of robust, liquid markets and what they mean for investment. So, the survey responses do not necessarily indicate that respondents do not see these issues as important, but that they see these issues as lower in *relative* importance to the other factors.

As indicated in Figure 4 regarding Question 3, the rankings relating to policy actions to expand hydrogen are relatively concentrated, with the average rankings between 3.4 and 6.5. The results reiterated that a multipronged approach is considered the most effective strategy, a sentiment that was also reinforced in the working group discussions.

Figure 4. Survey Responses to Question 3 (Average and One Standard Deviation)



Source: Authors.

Consistent with Question 2, the respondents saw designating sustained financial support for low- and zero-carbon hydrogen production technologies as the most critical policy driver. (Notably, the introduction of the 45V tax credit in the Inflation Reduction Act, which offers a graduated tax credit that rises as the carbon intensity of the hydrogen production technology declines, was passed after the survey was conducted.) Respondents ranked expanding the existing 45Q tax credits for carbon capture as second and designating regional hydrogen hubs as third. Collectively, the top three choices reflect an overall perspective among survey respondents that federal support through subsidy and/or direct market engagement is critical for advancing low-CO_2 hydrogen production technologies more quickly.[18]

Public-private partnerships, a low-carbon fuel standard (LCFS) or something similar, and permitting reform round out the top six choices. A LCFS, while in the middle of the pack, also had the widest range of responses, ranging from the top priority to the lowest priority. This reflects a substantial variation in the working group's discussions about the effectiveness of such a policy as a hydrogen market enabler, especially when compared to other options presented.

Harmonization of safety standards, regulatory requirements for firm sales commitments for intermittent resources, and open-access requirements on infrastructure round out the rankings from the survey regarding actions that policymakers could take to promote investment in and growth of a hydrogen market. As stated above, the working group discussions did not discount the importance of any of these matters. So, the rankings reflect a prioritization of actions as hydrogen markets evolve. In turn, engaging these issues will likely be important as investments are incentivized and projects move forward at scales beyond the existing market footprint.

In Question 4, we asked the respondents to define "hydrogen hub" in their own words. A selection of responses are given in Table 4. The responses indicated a diversity of definitions with some overlapping characteristics and themes.

Table 4. Select Survey Responses to Question 4

In your own words, define "hydrogen hub."
• An area with proximity to robust demand markets and ready supply access along with storage and other ancillary services, where multiple buyers and sellers can readily transact — and frequently enough that fair market prices can be discerned.
• A hydrogen hub is a market center where traditional hub services — such as parks and loans — can be accessed. It is a place where physical markets clear and financial derivatives can be valued.
• Either a production hub or a usage hub.
• Bringing hydrogen value chain together in a coordinated manner, starting with a core group of vital components and then expanding outward.
• Large concentration of potential H_2 consumers with sufficient infrastructure and siting for that demand to be served by new H_2 supply.
• A geographical location where all (or a majority) of the necessary elements of the value chain are present to produce, transport, store, consume, and export hydrogen.
• A region or area with reasonable access to technology, applications, and infrastructure to yield quicker scalability of hydrogen value chain.
• Geographic collection of interacting hydrogen supply chain infrastructure.
• A region where large volumes of H_2 are produced and used in a way to promulgate the energy transition to low carbon.
• Supply and demand in close proximity.
• A network of hydrogen sources/producers, hydrogen demand/users, and connecting infrastructure (pipelines and storage).
• A geographic area in which the hydrogen value chain is concentrated and integrated such that economies of scale and scope are realized (i.e., the fixed costs of the associated infrastructure are leveraged across multiple participants and over multiple types and end-uses of hydrogen).
• An industrial cluster of hydrogen generation and production as well as uses for hydrogen as a feedstock for industrial activity and infrastructure to enable distribution to other markets.

Source: Authors.

Among the defining characteristics mentioned were, in no particular order, 1) co-location of supply and demand, 2) high density of connecting infrastructure (pipelines), 3) a market center with traditional hub services, 4) a cluster of hydrogen-focused industrial activity, 5) significant production of hydrogen, 6) large and concentrated demand for hydrogen, 7) sufficient infrastructure across the value chain, 8) the existence of a competitive market price, 9) involvement from multiple parts of the value chain, 10) a location that realizes economies of scale, and 11) a region of concentration with reasonable access to technology, applications, and infrastructure. Such a wide range of responses indicates that some differences may emerge with regard to policies that are oriented toward hub formation, particularly regarding the points of emphasis in any permitting decisions or appropriations.

VI. Hydrogen Hubs, Clusters, and Valleys

Hydrogen production and use have been central to certain activities — such as oil refining, fertilizer production, food processing, rocket fuel, and fuel cell applications — for years. So, it is not a new fuel, nor is the production technology and transportation technology untested. In fact, in regions where hydrogen production, transport, and use have been occurring (typically in large industrial corridors), there is an existing backbone of infrastructure on which to build.

Recently, hydrogen has been recognized as a potential stalwart to a pathway for decarbonizing energy use in heavy industry and transportation. Currently, however, almost all hydrogen is either produced via steam-methane reformation that uses natural gas as a feedstock (so-called “grey” hydrogen), or obtained as a by-product of other chemical processes, neither of which is carbon neutral. Moreover, because of its history, the hydrogen market is very regionalized and relatively immature, especially when compared to other energy markets. For instance, in 2019, the net hydrogen demand at Texas Gulf Coast refineries totaled 68,000 barrels per day, representing roughly one-third of the U.S. total.[19] In fact, almost two-thirds of hydrogen infrastructure in the U.S. is along the Texas Gulf Coast, with refinery use accounting for the bulk of the demand serviced by infrastructure.

Of course, hydrogen’s story in energy transitions is currently being written. There is still much to understand regarding things that include, but are not limited to,

- the manner in which different production technologies compete;
- the need for new production, transportation, and energy delivery infrastructures;
- the ability to leverage existing infrastructure for hydrogen market expansion;
- the ability to site and develop new infrastructures;
- the evolution of policy support and regulatory architecture; and
- the demand pull that will emerge from consumers for different uses of hydrogen, from industry to freight and/or passenger transportation to power generation.

Ultimately, a deep and liquid market will need to emerge, with adequate storage capacity to facilitate smooth market function. How these matters are resolved will ultimately tell the story of hydrogen in energy transitions.

a. What Is a Hub and What Are Hub Services?

A hub provides two key functions for a market: liquidity and de-risking market entry. Understanding the key elements required for a functional hydrogen hub is critical when shaping policies to enable hydrogen market expansion. So, we must define *hub* and *hub services*. From the survey of participants in the Baker Institute Working Group and the review of existing literature, national strategies, and cooperative agreements, we see multiple definitions applied.

The IIJA defines a "regional clean hydrogen hub" as "a network of clean hydrogen producers, potential clean hydrogen consumers, and connective infrastructure located in close proximity." The definition broadly includes the physical facilities of a hub without identifying the relevant services and intangible requirements necessary to ensure the long-term impact of a clean hydrogen hub intended by the IIJA. Moreover, it does not address the physical and/or financial liquidity that is necessary to de-risk market participation and investment. The existence of physical infrastructure is *necessary* but not *sufficient* to ensure hub services emerge.

We can draw lessons from the U.S. natural gas market, which began developing market centers in the late 1980s. Today, there are numerous natural gas hubs in the United States.[20] A density of interconnecting infrastructure (i.e., pipelines, storage, offtake, etc.) is a defining characteristic of each hub, which brings physical liquidity to each location. In turn, arbitrage is possible at each location, and market depth is enhanced by the rules governing market structure. Physical liquidity begets financial liquidity and price transparency, which de-risks market entry.

In this context, a natural gas market center, or hub, is defined as a physical point that "provides customers (shippers of natural gas) with (1) receipt and delivery access to two or more pipeline systems, (2) transportation services between these points, and (3) administrative services that facilitate the movement of gas and transfer of ownership."[21] These characteristics underline one of the critical functions of hubs — providing liquidity. So, a functional, long-term hub will see continued flows of the underlying commodity.

Another essential function of a hub is to encourage competition. This generally follows with reduced barriers to entry, robust trading capabilities, and open-access transportation and storage services. Altogether, this allows buyers to pursue the least-cost source of supply, just as it allows suppliers to receive the highest possible bid. This is a critical function that transparency brings to the market, thus facilitating market depth and reducing transaction risk.

Table 5 includes the traditional hub services that facilitate natural gas hub operation.[22] Notably, services such as parking, loaning, and peaking offer greater short-term flexibility at the hub in addition to conventional market services such as transportation and storage. Under an efficient market mechanism, the variety of services at a hub would develop organically based on the unique environment in each hub location. We return to the organic development of natural gas hubs in the U.S. in a later section.

Table 5. Hub Services

Service	Description
Transportation/wheeling	Transfer of gas from one interconnected pipeline to another through a header (hub), by displacement (including exchanges), or by physical transfer over the transmission of a market center pipeline.
Parking	A short-term transaction in which the market center holds the shipper's gas for redelivery at a later date. Often uses storage facilities, but may also use displacement or variations in line pack.
Loaning	A short-term advance of gas to a shipper by a market center that is repaid in kind by the shipper a short time later. Also referred to as advancing, drafting, reverse parking, and imbalance resolution.
Storage	Storage that is longer than parking, such as seasonal storage. Injection and withdrawal operations may be separately charged
Peaking	Short-term (usually less than a day and perhaps hourly) sales of gas to meet unanticipated increases in demand or shortages of gas experienced by the buyer.
Balancing	A short-term interruptible arrangement to cover a temporary imbalance situation. The service is often provided in conjunction with parking and loaning.
Title Transfer	A service in which changes in ownership of a specific natural gas package are recorded by the market center. Title may transfer several times for some natural gas before it leaves the center. The service is an accounting or documentation of title transfers that may be done electronically, by hard copy, or both.
Electronic Trading	Trading systems that either electronically match buyers with sellers or facilitate direct negotiation for legally binding transactions. A market center or other transaction point serves as the location where gas is transferred from buyer to seller. Customers may connect with the hub electronically to enter gas nominations, examine their account position, and access e-mail and bulletin board services.
Administration	Assistance to shippers with aspects of natural gas transfers, such as nominations and confirmations.
Compression	Provide compression needed to increase pressure of natural gas received off of a lower-pressure system so that it can be transferred to a pipeline operating at a higher pressure. If needed, additional compression is bundled with transportation, it is not a separate service.
Processing	The removal of liquefiable hydrocarbons and impurities from gas.
Risk Management	Services that relate to reducing the risk of price changes to gas buyers and sellers, for example, exchange of futures for physicals.
Hub-to-Hub Transfers	Arranging simultaneous receipt of a customer's natural gas at a connection associated with one center and simultaneous delivery at a connection associated with another center.

Source: Information from Energy Information Administration (EIA), "Natural Gas Market Centers and Hubs: A 2003 Update," October 2003, https://www.eia.gov/naturalgas/archive/mkthubs03.pdf.

b. Regional Differences in the Definition of a Hydrogen Hub

According to the International Energy Agency (IEA)'s Global Hydrogen Review[23], 16 countries (excluding the United States) had developed national hydrogen strategies as of 2021. Many countries have set specific targets for things such as electrolysis capacity, percentage of hydrogen in total energy consumption, the fleet size of FCEVs, and the refueling infrastructure for FCEVs. Countries with ample renewable resources, such as Germany, are focusing their national production strategies on electrolysis with renewables (green hydrogen), while others with limited resources, such as Japan and South Korea, aim to scale blue hydrogen production with natural gas and CCUS. Other regions, such as the U.S., have adopted policies that favor lower CO_2 intensity while remaining more or less agnostic on the production technology. Such an approach largely reflects the regional variations in resource availability and existing industrial footprints that exist across the U.S. Regardless of targets for production technologies across countries and regions, a lack of previous large-scale adoption of hydrogen means there is a dearth of existing infrastructure to leverage for growth, which presents a significant challenge for establishing a low-carbon hydrogen economy. Creating a domestic market is widely identified as a priority for hydrogen expansion. For that reason, coupling the establishment of hydrogen hubs with financial incentives has been prescribed by many national and regional governments as a market development strategy. As indicated in Table 2 and Section V, a non-exhaustive list of national and subnational hydrogen strategies worldwide and a survey of U.S. hydrogen stakeholders, respectively, indicates variation in the definitions of a hydrogen hub and the actions needed for hydrogen hub development.

Despite differences in details on hydrogen hubs across regions and stakeholders, there are common themes among the groups. Overall, the collective characteristics amount to geographic aggregation of components of the supply chain, including 1) large, diverse demand centers for hydrogen with multiple end-use applications, 2) co-location of large-scale production technologies and capability with demand centers, and 3) the presence of adequate infrastructure for hydrogen transport and storage. By aggregating the entire value chain, hydrogen hubs are expected to achieve economies of scale, minimize infrastructure costs, promote cost-sharing among market participants, and drive substantial physical liquidity. The regions around hubs can then benefit by concentrating innovation efforts and facilitating the workforce development necessary to expand the hydrogen industry. The ongoing or planned government actions to accelerate hub development primarily focus on selecting locations and providing financial support to encourage investment and build the required infrastructure.

The Australian government commissioned a study in 2019 detailing key factors influencing hydrogen hub siting and has identified more than 30 ports as potential hub locations.[24] As of April 2022, 16 different clean hydrogen hub projects had been funded under its Clean Hydrogen Industrial Hubs Program. In other regions, governments are pursuing public-private partnerships in the form of consortia or joint ventures as well as international partnerships for trading opportunities. For instance, the Aberdeen Hydrogen Hub is a joint venture between the city of Aberdeen and BP. The consortium approach is central to national strategy in the U.S. as well, which we elaborate on later.

It is important to note that the intangible infrastructure (such as a regulatory framework, an open-access and competitive market structure, and codes and standards) is either being developed in silos at the national level or is altogether missing from hub development strategies. A regulatory environment that is attractive to investment will ensure a fair and competitive market and is capable of adapting to future hydrogen production technologies and end-uses. In fact, this is critical to the development of a hydrogen economy. Interestingly, the Port of Rotterdam is the only hub project that explicitly ensures open- or public-access infrastructure, i.e., its backbone hydrogen pipeline. However, the open-access guarantee is limited to facilities in the port area.

Interestingly, some countries do not include hydrogen hubs in their national strategies. The concept of hub development in these countries is driven at the regional or local level. Such a bottom-up approach contrasts with the top-down strategies being undertaken in other countries, which begs an interesting question: Should hydrogen hubs be designated and planned into a national network, or should they develop locally and organically? Ultimately, either of the two strategies may work, which is acceptable as long as the efforts lead to an environmentally and financially sustainable, low-carbon hydrogen market.

VII. Competition and Growth: Natural Gas Market Lessons for Hydrogen?

Competition increases efficiency and drives market development. Removing barriers to entry is critical to introducing and fostering competition, which can have virtuous impacts for market growth. To effectively develop and deepen the existing hydrogen market in the U.S., which is heavily centered in the Texas Gulf Coast, there are steps that can be taken to enhance market liquidity. For example, one such step involves establishing a market structure that requires an unbundling of pipeline and storage capacity rights from facility ownership through rate-based, open-access transportation and storage services. Publicly accessible distribution and storage infrastructure de-risks entry for both suppliers and consumers who are seeking to access a hydrogen market but do not currently own and/or operate any pipelines or storage capacity. Of course, ownership must be fairly compensated in the market, and rate design should be developed in a way that encourages future infrastructure investment, but the introduction of competition will promote transparency, improve market efficiency and liquidity, maximize infrastructure utilization, and encourage entry.

This concept is not new to the development of the hydrogen industry. Internationally, a report commissioned by the Australian government in 2019 recommended regulatory responses with new or existing legislation to support the development of the hydrogen industry by ensuring 1) public access to existing infrastructure and 2) competition within the industry.[25] Similarly, the Port of Rotterdam guarantees open access to the infrastructure for hydrogen and CO_2 transport and underground storage throughout the port area. The Port and Gasunie are currently constructing the “backbone” hydrogen pipeline, which is expected to be operational by 2024.[26]

Establishing the open-access requirement for pipeline transmission and storage services to foster market competition was successfully executed in the U.S. natural gas market. Long-haul, interstate natural gas pipelines in the U.S. were originally developed under a system of natural monopoly, i.e., high fixed-cost barriers to entry with economies of scale. Companies such as Natural Gas Pipeline Company of America, ANR Pipelines, Tennessee Gas Pipeline, Texas Eastern Transmission Company, Florida Gas Transmission, Columbia Gas Transmission, Pacific Gas Transmission, Transcontinental Pipeline, El Paso Natural Gas, and others coordinated the transportation and sales of natural gas to the end-user, sometimes all the way back to the wellhead. They built and operated long-haul pipelines to transport natural gas purchased from the producing regions directly to demand centers where gas was delivered to customers. These interstate pipelines became the backbone of the current natural gas market.

The 1978 Natural Gas Policy Act (NGPA) was the first step in redesigning the natural gas market in the United States. Prior to the NGPA, natural gas prices for volumes sold on interstate pipelines were controlled, which led to a predictable outcome where producers opted for intrastate sales first, contributing to shortages in states that not did have robust natural gas production. The NGPA eliminated price controls that had contributed to shortages of natural gas prior to its passing, and recognized the need for prices to adjust to reflect a market-clearing supply-demand balance.[27] The NGPA also assigned authority to the Federal Energy Regulatory Commission (FERC) to regulate interstate natural gas production and transmission. The NGPA resulted in pipelines signing up for long-term, “take-or-pay” contracts with producers to deliver supplies to consumers. The higher prices that followed incentivized new production.

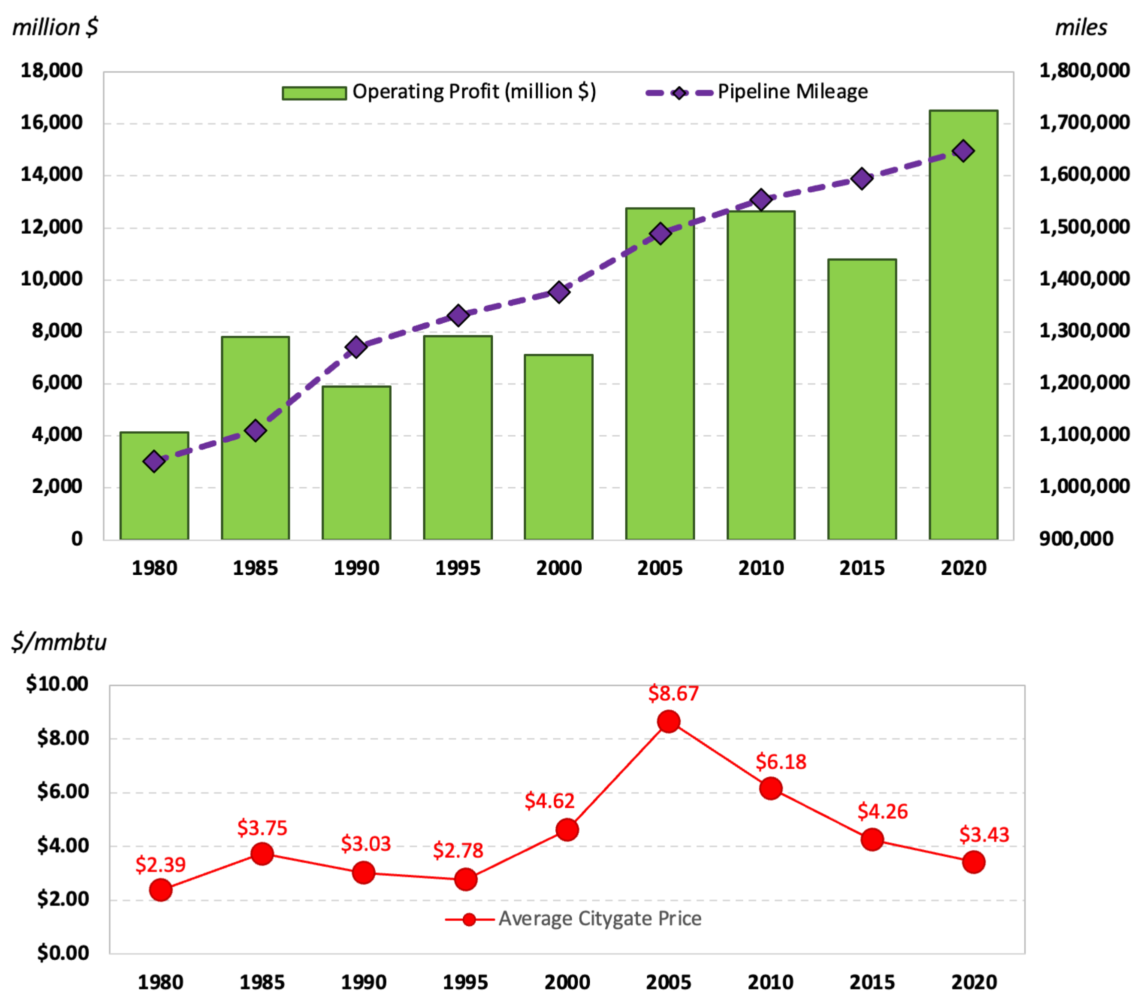
Over the subsequent two decades, a series of FERC orders completed the process of market restructuring. FERC Order 436, issued in 1985, allowed pipelines to voluntarily offer “open-access” transportation services on a competitive basis within a minimum and maximum tariff range. Customers realized cost savings relative to “take-or-pay” contracted volumes, so they switched. This left pipelines on the hook for take-or-pay contract commitments with producers, which eventually was settled in court. The pipelines were subsequently allowed to buy out the take-or-pay contracts and pass along costs to customers. In the end, new pricing paradigms, i.e., netback pricing, evolved in the U.S. market.

FERC Order 636[28] completed the restructuring of the natural gas market by unbundling capacity rights from the ownership of pipelines, requiring operators to provide comparable, non-discriminatory open-access services to all, so open-access was no longer voluntary. FERC also mandated the publishing of individual pipeline information to an Electronic Bulletin Board, thus establishing transparency on information to support market functions.

The restructuring that occurred in stages over two decades introduced competition into the natural gas market. As the process unfolded, not all stakeholders were aligned, with concerns emerging that restructuring would harm profitability.[29] However, restructuring has led to a deep, liquid natural gas market and improved efficiency of pipeline capacity utilization. Pipeline and storage capacity has expanded, which is a powerful indicator of what market liquidity can do to unlock the real option value of infrastructure. The growth of transparency spawned the emergence of regional spot and futures (both "over-the-counter" and on financial exchanges) markets. As competition in the natural gas market increased, market signals stimulated efficiency improvements and an ability to capture value from new rate structures, such as zonal systems for receipt, delivery, and pricing along interstate pipelines.

Figure 5 displays the operating profits of the pipeline industry since 1980, along with the mileage of pipelines and the annual average price of natural gas. FERC Order 636 went into effect in 1992. As indicated, the industry did not observe a drastic decline in operating profits after Order 636. In fact, the industry has seen growth.

Figure 5. Pipeline Operating Profits and Mileage, and Natural Gas Price, 1980-2020



Note: Data are indicated in "current" dollars.
Sources: Bureau of Transportation Statistics Database (www.bts.gov) and U.S. Energy Information Administration (www.eia.gov).

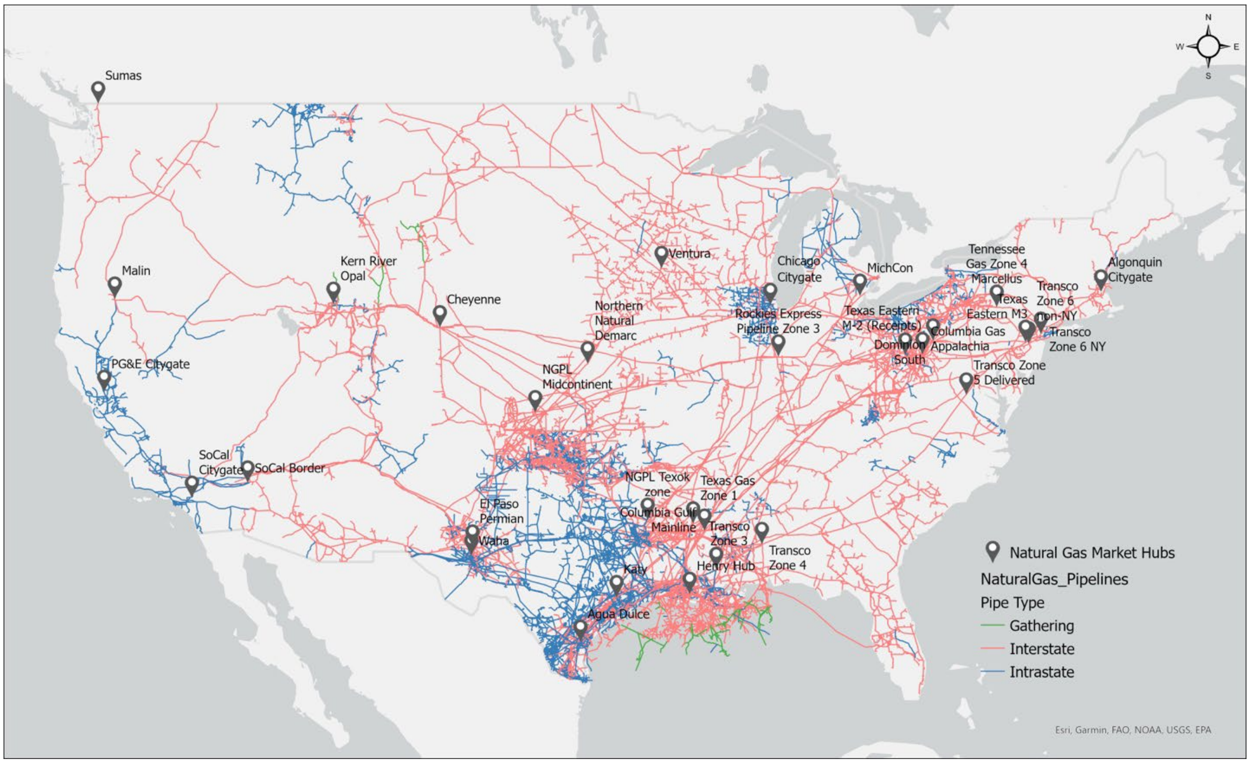
According to the Bureau of Transportation Statistics, the number of pipeline operators (not pictured) reported as “natural gas transmission” and “natural gas distribution” in 1970 were 420 and 938, respectively. By 1990, this number climbed to 866 and 1,382, respectively, and as of 2020 stood at 1,313 and 1,346, respectively. Thus, from a participation standpoint, the market is now roughly twice as deep today as it was in 1970, with a large fraction of that growth occurring after the NGPA was passed in 1978, which relaxed wellhead price controls so that market opportunity could be realized. Market participation and growth continued after 1990, with participation increasing by another 20%, infrastructure growing by about 30%, and operating profit expanding almost threefold. Notably, profitability has grown even after normalizing for the price of natural gas, which signals participants’ ability to capture market efficiencies, enabling sustained growth.

Competition brought the emergence of market hubs, which concomitantly promoted greater liquidity and market expansion. Moreover, these new market hubs became the locus for physical and financial transactions for natural gas. Hub services developed, including services such as parking, loaning, peaking, and balancing. This evolution added flexibility, allowed firms to manage costs differently, and formed the underpinning for new risk management capabilities.[30]

A hallmark of flexibility, hubs across the country have evolved in producing areas, demand regions, storage regions and at points of significant pipeline interconnectivity (see Figure 6). In sum, hubs tend to emerge in areas with greater physical market liquidity, i.e., a high number of market participants and hence trading opportunities. For example, Henry Hub, a physical distribution hub that interconnects several interstate and intrastate pipelines in southern Louisiana, is the most liquid natural gas hub in the nation and also serves as the point of settlement for financial trading on the NYMEX. Other hubs around the country — Chicago Citygate, SoCal Border, Waha, Dominion South, Algonquin Citygate, etc. — have been established at locations with access to significant storage capacity, large regional production volumes, and/or in areas where a large number of buyers are co-located. Notably, natural gas hubs emerged after the natural gas market was restructured, not before, and they did so as a result of transparency around gas flows and pricing, as well as ample trading opportunities due to a large number of market participants. The infrastructure is necessary but not sufficient for a market hub to form; regulation and market structure are equally important for the long-term viability of any market hub. In fact, this point translates to international market hubs, such as the Dutch Title Transfer Facility and the UK National Balancing Point.

A transparent, deep, liquid market reveals real option values of different infrastructures. In turn, this opens up opportunities that do not otherwise exist, largely because the option value presents a bankable proposition. Without this value proposition, contracts can be more cumbersome to negotiate because a specific counterparty must be identified, and the risk of any investment along the value chain is higher. This follows because there is a need to coordinate action by market participants along a value chain in order for any investment to occur. If any part of a supply chain fails — in the operational or investment phase — the entire supply chain fails. This is a prime example of "coordination failure." Hence, market participants are better served when the risk of coordination failure is reduced. This is precisely what a transparent, deep, liquid market does. By enabling market participants to invest in infrastructures that have a transparent value proposition to the entire market, investment capital is more available because the asset value is bankable.

Figure 6. Natural Gas Pipelines and Market Hubs in the U.S.



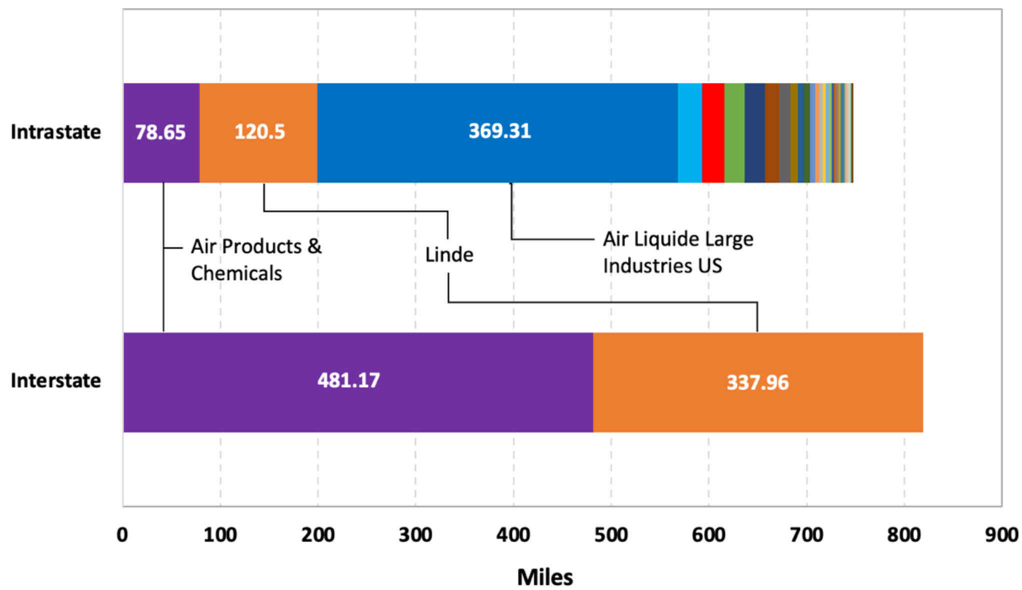
Sources: The map is constructed using ArcGIS Pro using data from U.S. Energy Atlas shapefiles available from the U.S. Energy Information Administration at Natural Gas Trading Hubs and Natural Gas Interstate and Intrastate Pipelines, respectively.

VIII. Hydrogen in the U.S.

a. *The Current and Evolving Landscape*

The current market structure in the domestic hydrogen pipeline system strongly resembles the pre-1992 natural gas pipeline industry, albeit at a much smaller scale. There are approximately 1,600 miles of hydrogen pipelines in operation across the U.S.[31] For comparison, there are over 3 million miles of natural gas pipelines.[32] Air Liquide, Linde, and Air Products own 89% of the existing interstate and intrastate pipeline mileage (see Figure 7).

Figure 7. U.S. Hydrogen Pipeline Mileage by Owner/Operator, 2021



Source: Data from Pipeline and Hazardous Materials Safety Administration (PHMSA).

This begs an important question: Why is the current hydrogen market relatively concentrated? Quite simply, because it has historically been focused on very specific industrial applications, such as crude oil refining and fertilizer production. As such, the market has been heavily focused geographically and by end-use sector. This tends to tie producers who can increase output and capture economies of scale to consumers who can contractually commit to large offtake agreements. In the absence of new entrants on the demand side who can create demand-pull for new production, or low-cost production technologies that can create competitive supply-push into new market applications, the market has evolved to be highly concentrated. When a market is thin, or has few market participants, direct connections between producers and consumers reduce transaction risks.[33] In turn, vertically integrated structures are favored because they reduce the number of parties required for a full supply chain to develop, thus reducing the risk of coordination failure.

Major suppliers of hydrogen operate as vertically integrated companies that own and operate facilities to manufacture, transport, store, and deliver hydrogen under long-term bilateral contracts with their customers. This has served the current hydrogen market well, particularly due to the relative lack of market participants. However, the potential for a deep market to form around a hydrogen hub will depend on its attractiveness to new entrants, the ability to connect to other regions, and the liquidity services the hub offers. This highlights a critical point: Infrastructure is *necessary* for hub formation, but it is not *sufficient*.

Given the fixed costs of expanding the hydrogen pipeline network versus potentially repurposing existing natural gas pipelines, there has been significant interest dating back at least a decade in using natural gas pipelines for transporting hydrogen[34] to support the commercial prospects of the various production technologies.[35] Of course, if natural gas is used as a feedstock for blue and turquoise hydrogen production, which is co-located with end-use applications, then the need for significant expansion of hydrogen pipeline infrastructure is reduced. But even with blue and turquoise hydrogen, takeaway capacity for captured CO_2 and/or solid carbon must be built. There are already efforts to significantly expand the use of carbon capture[36] across various regions of the U.S. where the potential for blue and turquoise hydrogen are greatest.

The emphasis on expanding hydrogen use varies across regions of the U.S., largely reflecting the comparative advantages driven by existing energy infrastructures and policy support. There are a number of federal incentives directed at hydrogen that include various tax credits and exemptions, loan program support, and zero-emissions incentives.

In 2018, the DOE established the H2@Scale initiative to bring together stakeholders "to advance affordable hydrogen production, transport, storage, and utilization to enable decarbonization and revenue opportunities across multiple sectors."[37] A technical report prepared by the National Renewable Energy Laboratory (NREL) that was funded by H2@Scale indicates U.S. demand for hydrogen could reach a total of 106 MTPA by 2050 across multiple applications — including light-duty FCEVs (21 MPA), natural gas supplementation (16 MTPA), seasonal energy storage for electricity (15 MTPA), and synthetic fuels (14 MTPA) — which is more than a tenfold increase from the current 10 MTPA of demand.[38] Since its launch, H2@Scale cooperative research and development agreements (CRADA) have resulted in more than 30 projects involving industry, academia, national labs, and non-profit organizations.[39] The projects are focused on hydrogen production (four projects), hydrogen infrastructure (16 projects), hydrogen safety, codes and standards (four projects), electricity grid integration (seven projects), and hydrogen end-uses (one project).

In 2021, the DOE surveyed thousands of respondents during the Hydrogen Shot Summit and found that costs to end-users, limited infrastructure, and lack of public understanding are the three largest barriers preventing public acceptance of the wide adoption of hydrogen. To help reduce barriers, the Biden administration launched the "Hydrogen Shot" as the DOE's first Energy Earthshot Initiative, with the target of reducing the production cost of hydrogen to $1 per 1 kilogram of hydrogen in one decade (2031) (the "1-1-1" target) in the IIJA.[40]

The IIJA launched five additional hydrogen programs — the Clean Hydrogen Research and Development Program (Sec.40313), the National Clean Hydrogen Strategy and Roadmap (Sec. 814), Clean Hydrogen Manufacturing and Recycling (Sec. 815), the Clean Hydrogen Electrolysis Program (Sec. 816), and Clean Hydrogen Production Qualifications (Sec. 822) — along with the aforementioned Clean Hydrogen Hub Program (Sec. 813).[41] Overall, the bill authorized $8 billion for the clean hydrogen hub program to establish at least four hydrogen hubs, $1 billion for demonstration projects in the clean hydrogen electrolysis program, and $500 million for research and development in the clean hydrogen manufacturing and recycling program. All funding streams are allocated through 2026. The Clean Hydrogen Hub Program and its $8 billion funding have accelerated hydrogen initiatives across the country that are led by both public and private sector stakeholders, with some states combining efforts.[42]

In December 2021, the DOE identified 10 regional clusters suitable for regional clean hydrogen hub sites.[43] In September 2022, the DOE published its draft National Clean Hydrogen Strategy and Roadmap.[44] The DOE roadmap prioritizes three strategies: 1) target strategic, high-impact uses for clean hydrogen, 2) reduce the cost of clean hydrogen, and 3) focus on regional networks. The last of these three strategic priorities is precisely where hubs come into focus. Moreover, the DOE highlights in its draft roadmap that coordination across other government agencies and "numerous stakeholder groups" is critical to success. Selected hubs will have a timeframe of eight to 12 years to establish a financially viable operation.

In June 2022, the DOE's Loan Programs Office announced a $504.4 million loan guarantee award to Advanced Clean Energy Storage in Delta, Utah, to construct the world's largest clean hydrogen storage facility.[45] This is the first clean energy project the Loan Program Office has awarded since 2014, reiterating the significance of hydrogen in the national policy agenda.

Most recently, the IRA introduced a production tax credit (45V) and investment tax credit (48) that has a sliding scale based on the CO_2 intensity of hydrogen production. The clean energy incentives in the IRA support clean hydrogen and fuel cell technologies by extending/increasing existing federal tax credits or creating new federal tax credits. Table 6 summarizes the federal hydrogen-related incentives in the IRA.

The IRA also provides $1 billion in funding for the EPA's Clean Heavy-Duty Vehicle Program.[46] The program is meant to distribute the funds through 2031, with $400 million designated for communities in non-attainment areas. The program is targeted to "replace dirty heavy-duty vehicles with clean, zero-emission vehicles, support zero-emission vehicle infrastructure, and to train and develop workers."

There are also state-level incentives aimed at increasing the use of hydrogen.[47] For example, California's LCFS provides a significant boost to hydrogen, so much so that it is often raised as a potential policy prescription in other regions, although the reception varies by state. In fact, California has more laws and incentives in place directed at hydrogen than any other state, so it should not be surprising that it also leads the nation in hydrogen fueling locations.[48] Toyota has been testing hydrogen in heavy-duty applications in the Port of Los Angeles since 2017 and is actively marketing its Mirai hydrogen fuel cell vehicle for personal transport. Companies such as Air Liquide have been developing hydrogen production with an aim to serve the California market. While efforts are also underway in other parts of the country, the significant policy support in California has accelerated non-traditional uses of hydrogen in the state relative to other regions.[49]

Table 6. Federal Hydrogen Incentives in the IRA[50]

<table>
<tr><th>Advanced Energy Project Credit</th><th>Extension, 48C</th></tr>
<tr><td colspan="2">• Extends the 30% investment tax credit
• Creates funding for manufacturing projects producing fuel cell electric vehicles, hydrogen infrastructure, electrolyzers, and a range of other products
• Expands tax credit to projects at manufacturing facilities that aim to reduce GHGs by at least 20%
• Tax credit is funded at $10 billion for eligible projects
• Applied to retrofitting facilities for low-carbon industrial heat, CCUS systems, and equipment for recycling, waste reduction, and energy efficiency</td></tr>
<tr><th>Alternative Fuel Refueling Property Credit</th><th>Extension, 30C</th></tr>
<tr><td colspan="2">• Extends tax credit to property placed into service before 2033
• Increases tax credit to 30% of the cost of alternative fuel refueling property up to $100,000
• Eliminates restriction to allow for the credit to be used only once so that taxpayers who install qualified equipment at multiple sites are allowed to use the credit toward each site location
• Includes new census tract restrictions for development in low-income and rural communities</td></tr>
<tr><th>Carbon Capture and Sequestration Credit</th><th>Extension and increase, 45Q</th></tr>
<tr><td colspan="2">• Enhances the tax credit for carbon capture and direct air capture
• Extends the deadline for construction to January 1, 2033, and increases the credit amount</td></tr>
<tr><th>Clean Hydrogen Production Tax Credit</th><th>New, 45V</th></tr>
<tr><td colspan="2">• Creates a 10-year clean hydrogen production tax credit (PTC) worth up to $3.00/kilogram. Projects can also claim up to a 30% investment tax credit under Section 48. The credit is based on CO_2 intensity, such that:
<table>
<tr><th>CO_2 Intensity (kg CO_2/kg H_2)</th><th>Maximum PTC ($/kg H_2)</th></tr>
<tr><td>4.0-2.5</td><td>$ 0.60</td></tr>
<tr><td>2.5-1.5</td><td>$ 0.75</td></tr>
<tr><td>1.5-0.45</td><td>$ 1.00</td></tr>
<tr><td>0.45-0.0</td><td>$ 3.00</td></tr>
</table>
• Projects must begin construction by 2033, and retrofit facilities are eligible
• Cannot stack with the Carbon Capture and Sequestration Tax Credit (45Q)
• Can stack with renewable energy production tax credit and zero-emission nuclear credit
• Projects must promote good-paying jobs to receive the full credit</td></tr>
<tr><th>Elective Payment for Energy Property</th><th></th></tr>
<tr><td colspan="2">Allows direct payments to be made in lieu of a reduction in tax liability (“direct pay”) and/or an option to monetize the credits by transferring them to an entity with greater tax liability (“transferability”). Direct pay is limited to certain tax-exempt and governmental entities for most of the eligible tax credits. This limitation does not apply to the first five years of the section 45V clean hydrogen credit, section 45Q carbon capture and sequestration credit, and section 45X advanced manufacturing credit. Direct pay expires at the end of 2032.</td></tr>
<tr><th>Energy Credit</th><th>Extension, 48</th></tr>
<tr><td colspan="2">Extends the 30% fuel cell investment tax credit through 2024 before a transition to the technology-neutral Clean Energy Investment Credit, which begins in 2025. Can receive a bonus for domestic-sourcing of materials and for siting projects in “energy communities.”</td></tr>
</table>

Energy Storage Credit	**New, 48**
Adds a new provision to the energy investment tax credit for energy storage, including hydrogen storage, available through 2025 before a transition to the Clean Energy Investment Credit.	
Clean Vehicle Credit	**New, 30D**
• Maintains the existing $7,500 for the purchase of fuel cell electric vehicles by creating a qualified new clean vehicle credit built on the 30D credit for plug-in battery electric vehicles • Adds a retail price cap of $55,000 for new cars and $80,000 for pickups, vans, and SUVs • Credit is reduced if a certain percentage of the critical minerals utilized in battery components are not extracted or processed in the United States or a Free Trade Agreement country or recycled in North America; the required percentage increases from 40% in 2024 to 80% in 2026 • Credit is reduced if electric vehicle is not assembled in North America or if the majority of battery components are sourced outside of North America; the required percentage increases from 50% in 2024 to 100% in 2028 • Implements an income eligibility limit of $150,000 per individual, or $300,000 for joint filers • Eliminates the tax credit phase-out for manufacturers as they near 200,000 clean vehicles sold	
Qualified Commercial Clean Vehicles Credit	**New, 45W**
Creates a new 30% credit for commercial fuel cell electric vehicles through 2032, capped at $40,000. • For class 1–3 (under 14,000 lb.) vehicles for commercial use, creates a $7,500 tax credit tax for the purchase of electric vehicles or other qualified clean vehicles • For class 4 and above (over 14,000 lb.) vehicles for commercial use, increases the credit to $40,000	

Source: Information gathered from "Financial Incentives for Hydrogen and Fuel Cell Projects," Hydrogen and Fuel Cell Technologies Office, U.S. Department of Energy, https://www.energy.gov/eere/fuelcells/financial-incentives-hydrogen-and-fuel-cell-projects.

In traditional oil- and gas-producing regions that also have large chemical and petrochemical sectors, hydrogen is gaining a significant amount of attention from regional port authorities, industrial energy consumers, local political leadership, and the oil and gas industry. For example, in Texas, which has long been associated with oil and gas, the sustainability of the regional economy is driving interest in hydrogen pathways, especially those involving hydrocarbon feedstocks while eliminating CO_2. Texas already has a large industrial complex with a sizeable hydrogen footprint, which is an enabler, and the number of studies, focus groups, and pilot programs is growing rapidly.

Policy can play a formative role. Public funding (through direct subsidy or tax credit), mandates, and low-carbon fuel standards all play a formative role. But perhaps the most transformative actions would be de-risking investments through pilot programs and/or support for infrastructure and hub development. Hubs are enablers because they reduce barriers to entry by mitigating the risk of offtake for investors upstream of the market hub, as well as reducing the risk of access to supply downstream of the market hub. In turn, this promotes liquidity and, hence, greater investment. However, as noted above, while supporting infrastructure development is an important step in the journey to hub development, for a liquid *market* hub to emerge, the regulatory environment must be addressed to promote transparency and reduce barriers to entry.

b. Federal Regulation

Despite the advances in federal funding support for hydrogen infrastructure and incentives to promote demand, clear and comprehensive regulations for hydrogen systems are still needed. New hydrogen infrastructure is not only subject to local/state authority, but could also be subject to federal oversight and would certainly be required to uphold minimum federal standards for safety and environmental performance. In order to integrate hydrogen into existing energy systems, many of the regulations required for hydrogen are likely to fall within, or be derived from, existing regulations for natural gas systems.[51]

The EPA is the sole federal agency with regulatory oversight of the production of hydrogen, and its regulations extend only to emissions. Title 40, Part 98 of the Code of Federal Regulations (CFR) on Mandatory Greenhouse Gas Reporting defines hydrogen production facilities and the required emissions reporting threshold.[52]

Regarding the transportation of hydrogen on pipelines, there is limited federal oversight. The Office of Pipeline Safety within the Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA) regulates the safety aspect of interstate hydrogen pipelines under Title 49, Part 190-199 of the CFR, where "gas" is defined as "natural gas, flammable gas, or gas which is toxic or corrosive." Under the Natural Gas Policy Act of 1978, Title 18, Part 153 of the CFR regulates the filing requirement for siting, construction, and operation of import and export facilities of natural gas,[53] and Title 18, Part 284 of the CFR regulates the siting, routing, and construction of interstate natural gas pipelines as well as the distribution and sale of interstate natural gas.[54] However, these provisions are limited to natural gas only. Hence, FERC does not have direct authority over interstate or intrastate hydrogen transportation and sales via pipeline, nor does it have authority over hydrogen import/export facilities. This means that new hydrogen pipeline projects must seek siting approval from state authorities, which will likely require multiple approvals for systems that cross state borders.

Besides dedicated hydrogen pipelines, transporting pure hydrogen or a hydrogen-natural gas blend in existing natural gas pipeline systems is also being considered. Research suggests current gas pipelines and end-use appliances can tolerate up to 15%-20% of hydrogen blend without significant retrofitting.[55] There are initiatives, such as DOE's HyBlend, that evaluate the technical barriers concerning blending hydrogen in existing natural gas pipelines.

In 2021, FERC asserted authority over hydrogen-gas blends transported via interstate gas pipelines. However, uncertainty persists regarding the scope of its jurisdiction and the threshold of hydrogen percentage in the hydrogen-gas blend before the pipeline is no longer considered a natural gas pipeline but instead a hydrogen pipeline. While technical and economic feasibility regarding the extent to which hydrogen can be blended and transported via today's natural gas pipelines is still being investigated, the lack of hydrogen provisions in the existing FERC authority over interstate gas pipelines poses significant uncertainty when considering blending or pipeline conversion. Currently, no gas quality and interchangeability standards are dedicated to addressing hydrogen-gas blends or pure hydrogen according to FERC's policy statement on natural gas interchangeability.[56]

Significant gaps in federal oversight also exist in other parts of the hydrogen value chain. For example, federal regulations on residential and commercial heating by FERC and the Office of Energy Efficiency and Renewable Energy are fuel-specific and currently only explicitly mention natural gas and propane. Where there is federal authority over a particular segment of the hydrogen value chain, hydrogen is primarily regulated under hazardous materials safety protocols of various agencies. For instance, the use of hydrogen as a fuel source for road vehicles or the distribution of hydrogen via truck, rail, and waterway is overseen by the PHMSA, the Federal Highway Administration, the Federal Transit Administration, the U.S. Coast Guard, and the Occupational Safety and Health Administration.

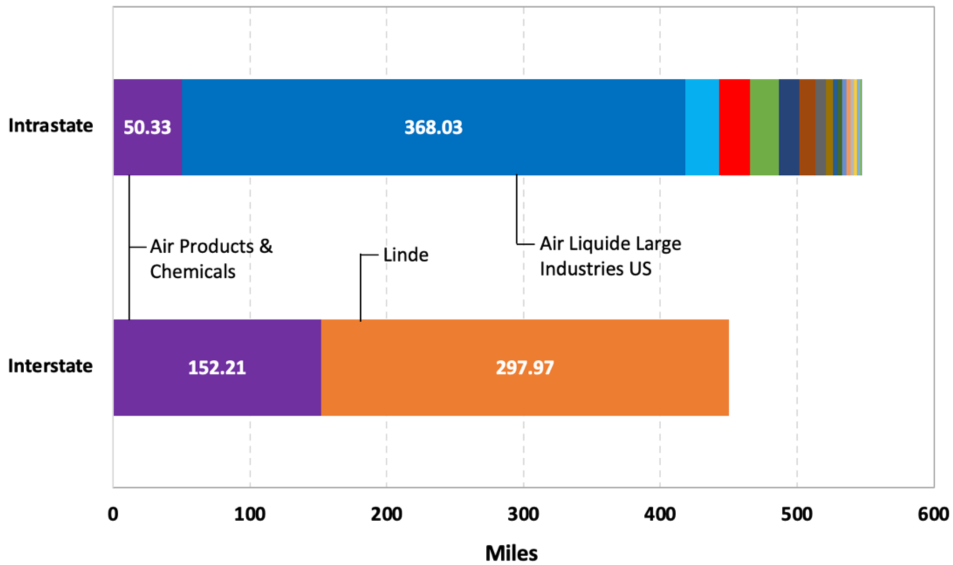
A well-conceived national regulatory framework for hydrogen could reduce uncertainty and lower barriers to market entry while ensuring hydrogen safely integrates into existing energy systems. This would also allow room for growth and new technology adoption. Pipelines will play a crucial role in encouraging competition and trade across regions. In turn, this would facilitate the creation of a national hydrogen economy, benefitting market depth and liquidity.

IX. A Focus on Texas

a. Infrastructure and Market Potential

Texas has tremendous potential to take a leadership role in building the hydrogen economy. The region has an existing backbone hydrogen infrastructure. Today, there are almost 1,000 miles of hydrogen pipelines in Texas alone, representing 64% of the total mileage in the U.S. Three of the largest industrial producers of hydrogen — Air Liquide, Linde, and Air Products — are owners of 87% of the hydrogen pipeline mileage in the state.[57] Sixteen other companies operate the remaining 13% (see Figure 8).[58] Hence, Texas already has the necessary infrastructure to become a successful hydrogen hub. The already active hydrogen supply chain in the Texas Gulf Coast presents an ideal location for market acceleration, and the co-location of abundant renewable and natural gas resources and robust CCUS capabilities reinforce this potential.

Figure 8. Texas Hydrogen Pipeline Mileage by Owner/Operator, 2021

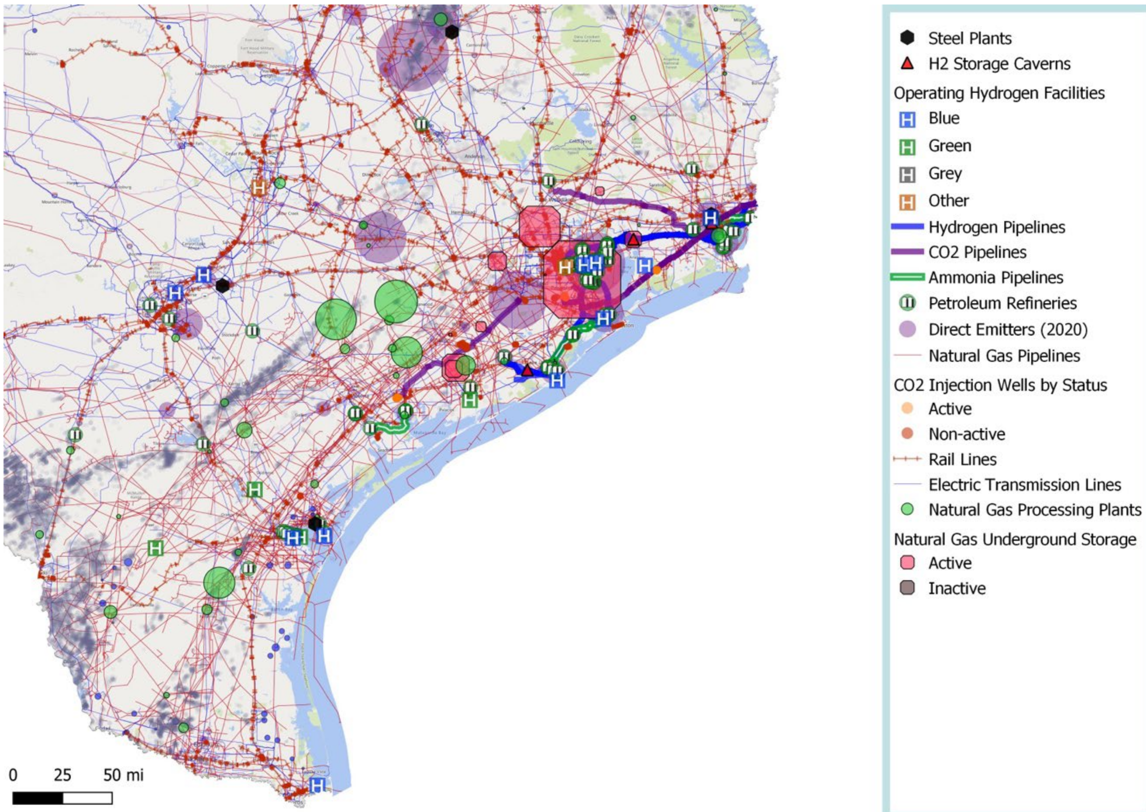


Source: Data are from PHMSA.

The scale of current hydrogen activities in Texas is significant. Out of the 140 hydrogen production facilities currently operating in the U.S., approximately one-third of those plants (43) are located in Texas. All but one facility in Texas produces grey hydrogen either via steam methane reforming or as an industrial byproduct. Air Liquide, Air Products, and Linde, combined, operate 42 of the 43 operating plants. Currently, petroleum refineries in Texas alone produce about 2 MTPA,[59] or approximately 20% of current national production.[60]

Figure 9 is a map that shows existing infrastructure relevant to the hydrogen sector in the Texas Gulf Coast. The density of infrastructure is an indicator of the hydrogen backbone that carries great potential for the region. Indeed, the Texas Gulf Coast has a well-established infrastructure network along the hydrogen supply chain. Relevant facilities include hydrogen production plants, hydrogen pipelines, hydrogen storage facilities (all three in Texas are salt caverns), petroleum refineries, ammonia pipelines, CO_2 pipelines and injection wells, and natural gas pipelines, processing plants, and storage facilities. Additional layers such as large GHG emitters, steel plants, electric transmission lines, rail lines, active oil and gas wells (grey shaded dots), and wind power plants (royal blue circles) are also included in the map.

Figure 9. Map of Existing Infrastructure in Texas Relevant to the Hydrogen Market



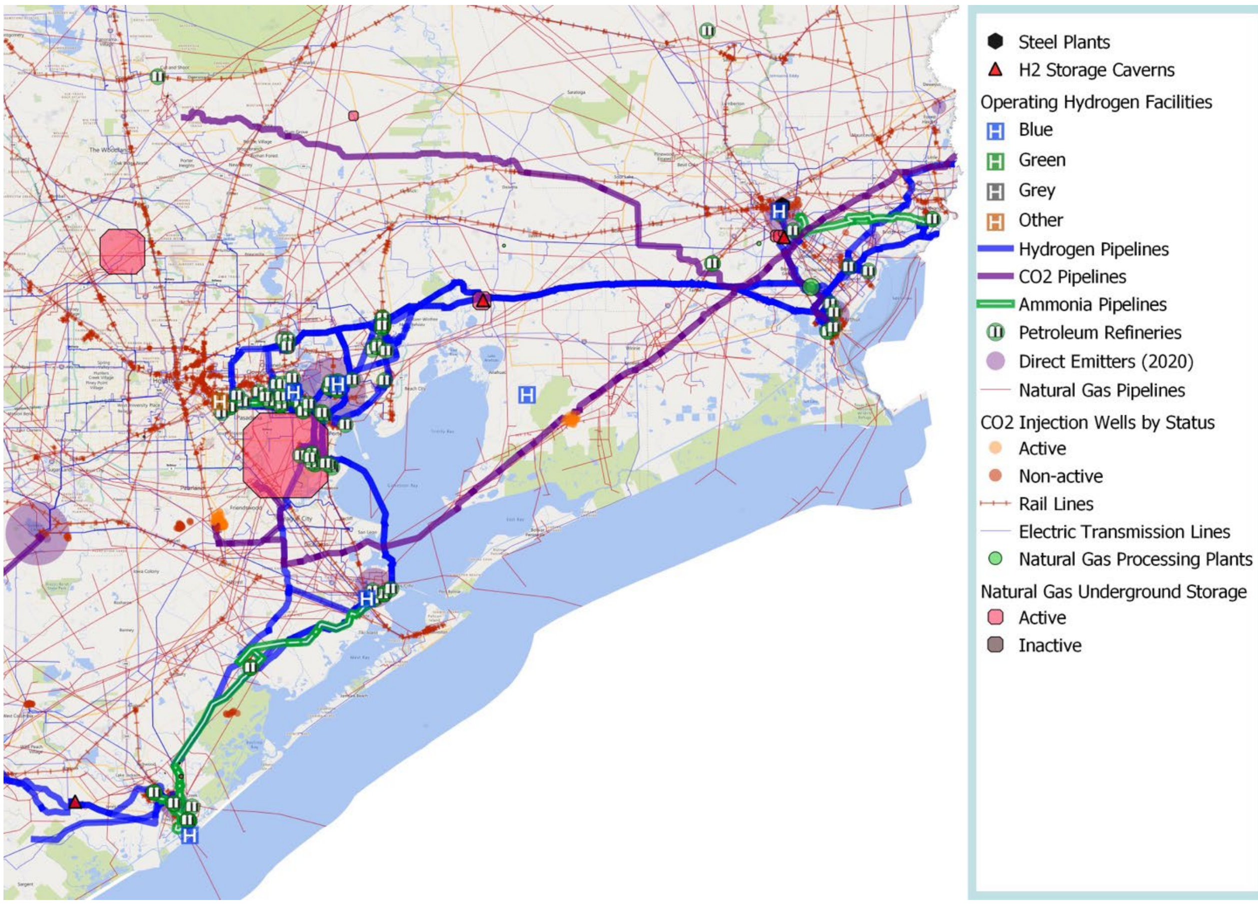
Sources: Data are taken from the Texas Railroad Commission, U.S. EIA, U.S. EPA, *Petroleum Economist*, Enverus, and authors' research. Mapping is done in QGIS.

Figure 10 provides a close-up of hydrogen infrastructure in the Texas Gulf Coast. As illustrated, the hydrogen infrastructure is primarily concentrated in the Houston Ship Channel region. Moreover, hydrogen production facilities are mostly co-located with petroleum refineries to meet the existing demand as feedstock. According to the U.S. EIA, Texas alone accounts for 32% of U.S. refining capacity. States in the U.S. Gulf Coast region collectively represent half of the petroleum refining capacity and natural gas processing capacity nationwide.

Three of the four currently operational hydrogen storage facilities in the world are located in Texas. The three sites in Moss Bluff, Spindletop, and Clemens are operated by Air Liquide, Linde, and Phillips, respectively. Air Liquide's facility is the world's largest hydrogen storage site.

Twenty additional hydrogen production facilities have been planned or proposed in Texas. Fourteen are blue, and four are green hydrogen. Considering the blue hydrogen pathway, Texas boasts comparative advantages in low-cost natural gas production, transportation, and delivery infrastructure, and has significant opportunities in CCUS with long-term storage potential in the state's offshore saline formations.[61] For the green hydrogen pathway, abundant wind power in Texas can be transmitted to the Gulf Coast thanks to a well-connected power market with adequate internal transmission capacity.

Figure 10. Map of Existing Hydrogen Infrastructure in the Texas Gulf Coast



Sources: Data are taken from the Texas Railroad Commission, U.S. EIA, U.S. EPA, *Petroleum Economist*, Enverus, and authors' research. Mapping is done in QGIS.

Indeed, many hydrogen projects are under development on the Gulf Coast. For instance, the U.S. start-up Green Hydrogen International is developing the Hydrogen City Project just west of Corpus Christi. The site includes production, storage, and pipeline facilities. When completed, the 60 GW project expects to produce 2.5 MTPA — using wind and solar power — as clean rocket fuel for SpaceX. Another example is ExxonMobil's Baytown hydrogen project. To achieve its ambition to be net-zero by 2050, the company is building a hydrogen plant in Baytown with one of the world's largest CCUS projects to fuel its olefin plant.

A recent report commissioned by the Center for Houston's Future and completed by McKinsey & Co. laid out the current hydrogen landscape for Houston and Texas.[62] The findings suggest multiple supply-side advantages and projects a 21 MTPA market by 2050 relative to the current estimated market of 3.6 MTPA from refining in the Texas-Louisiana Gulf Coast. Specifically, the report marks exports as a long-term driver, potentially providing 10 MTPA by 2050, or almost half of all production. The remaining projected demand in the region consists of 6 MTPA from industry, 3.8 MTPA in mobility, and 1.6 MTPA in power and heating. Current exports are very small, so growth in international trade will require significant infrastructure expansion.[63]

While the Texas state government has not proposed plans to establish hydrogen hubs, there are multiple private sector coalitions leading efforts to secure DOE funding to develop a hydrogen hub in Texas. The fact that these entities are competing with each other signals a broad recognition of the opportunity in the region.

Despite the intense interest in expanding the hydrogen market in Texas with a focus on deploying production technologies and infrastructure development, the relative infancy of a market that extends beyond specific legacy industrial activities presents some challenges, particularly with regard to regulation. A clearly defined regulatory framework that incorporates hydrogen into the existing energy system while ensuring safe operation and fair competition is crucial to effectively stimulate market development and encourage widespread adoption of hydrogen, as intended by recent policy incentives and growing industry actions.

b. Regulating Hydrogen in Texas: State

Any existing federal policy or regulation applies at the state level in Texas. But, at the state level, there are multiple additional touch-points with hydrogen through policy and regulation, including the Texas Railroad Commission (TXRRC), the Texas Department of Transportation (TxDOT), the Texas Commission on Environmental Quality (TCEQ), and the Public Utility Commission of Texas (PUCT).[64] As hydrogen uses expand and infrastructure requirements grow, siting and permitting plus basic market function will likely demand greater interaction across regulatory agencies and policymakers.

1. <u>Texas Railroad Commission (TXRRC)</u>

The TXRRC, established in 1891, is the oldest regulatory agency in Texas. It was originally responsible for regulating tariffs on railroads, but has since ceded this responsibility to other agencies, including TxDOT. Today, the TXRRC's regulatory responsibilities include the oil and natural gas industry, pipelines, natural gas utilities, and surface mining operations for coal and uranium. The agency also has regulatory jurisdiction for enforcing federal law on the Surface Coal Mining Control and Reclamation Act, Safe Drinking Water Act, Pipeline Safety Acts, Resource Conservation Recovery Act, and Clean Water Act.[65] Regarding hydrogen, the TXRRC's oversight is largely around safety and operations, with no real engagement on market structure, facility use and/or market oversight.
Regarding the potential for regulation of hydrogen pipeline transit specifically, as authorized by PHMSA, the Pipeline Safety Department of TXRRC is responsible for inspecting and enforcing the pipeline safety regulations for intrastate gas and hazardous liquid pipeline operators in Texas.[66] The authority of TXRRC over pipeline safety is established by the following:

- Texas Statutes Title 3. Gas Regulation
- Texas Statutes Title 5. Provisions Affecting the Operation of Utility Facilities
- TX Admin. Code (TAC), Title 16, Chapter 8 - Pipeline Safety Regulations
- TAC, Title 16, Chapter 18 - Underground Pipeline Damage Prevention

In addition, TAC Title 16, Chapter 3, Rule 3.7 requires all pipeline operators to file the T-4 Pipeline Permit with TXRRC to legally operate their facilities in the state.[67] The permit includes both interstate and intrastate pipelines and is to be renewed annually. Currently, hydrogen pipeline operators must check "other/specify" for fluid transported.[68]

TXRRC also oversees the permitting, construction, operation, and reporting of underground hydrogen storage facilities under the Texas Administrative Code. It regulates underground gas storage in salt formations, where gas is defined as "natural gas and any other gaseous substance."[69]

2. Texas Department of Transportation (TxDOT)

TxDOT was born as the Texas Highway Department in 1917, and was charged with building and maintaining roadways, as well as handling licensing and registration (tasks later given to the Texas Department of Public Safety and Texas Department of Motor Vehicles, respectively).[70] Today, the agency maintains the state's transportation infrastructure in order to "facilitate the movement of freight and international trade," support economic activity and transportation safety, and "ensure efficient use of state resources."[71]

In House Bill 2702 in 2005, Transportation Code Sec. 201.618 directs TxDOT to "seek public and private funding to acquire and operate at least (1) five hydrogen refueling stations, (2) four hydrogen combusted vehicles, and (3) three FCEV, one hydrogen bus, or one F.C. bus." The legislation also requires TxDOT to monitor the emissions from the fleet and refueling stations, which must be reported to TCEQ. However, the bill did not provide any financial support.[72] The same bill directed TxDOT to develop a strategic plan for hydrogen. TxDOT then sponsored the report, titled "TxDOT Strategic Plan for Hydrogen Vehicles and Fueling Station," published by the University of Texas in Austin in 2006.[73]

In 2019, the North Central Texas Council of Governments, along with agencies from four other states (IL, PA, TN, and AZ), received funding from the Federal Highway Administration to develop a plan for the Interstate Highway 45 to become a zero-emission vehicle corridor from Dallas to Houston.[74,75] The proposed Alternative Fuel Corridor,[76] representing almost half of Texas' truck freight, would serve both electric vehicles and hydrogen fuel cell vehicles, with a focus on medium- and heavy-duty trucks and buses. The plan's development is still in process at the time of writing, albeit the final submission was due by 2020.

More recently, TxDOT has been developing an Electric Vehicle Infrastructure Deployment Plan. The plan will be submitted to the Federal Highway Administration for funding authorized by the National Electric Vehicle Infrastructure Formula Program under the IIJA. However, the plan focuses on electric vehicles.

3. <u>Texas Commission on Environmental Quality (TCEQ)</u>

TCEQ is the environmental regulatory agency for Texas that "strives to protect our state's public health and natural resources consistent with sustainable economic development."[77] TCEQ's previous incarnation — the Texas Natural Resource Conservation Commission — was founded in 1993 by the Texas Legislature by combining other programs. In 2001, the Legislature changed the name to the Texas Commission on Environmental Quality.

While not directly regulating hydrogen market activities, TCEQ oversees permitting and environmental compliance on Texas air quality, water, and waste. As such, TCEQ has a formative role to play in the future of hydrogen in Texas with regard to the environmental attributes of various production technologies relative to each other and other energy sources. So, the commission's role in regulating various aspects of the hydrogen value chain is critical.

TCEQ administers five emissions banking and trading programs that allow participants to reduce emissions of nitrogen oxides (NO_x) and sulfur oxides (SO_x) throughout the state.[78] Programs such as the Mass Emissions Cap and Trade Program[79] set an annual allowance cap for NO_x emissions from regulated facilities in the Houston-Galveston-Brazoria ozone nonattainment area to ensure compliance with federal air quality standards. The regulated facilities must not violate their annual emissions cap utilizing their allowances or trading credits. Major hydrogen producers such as Air Liquide, Linde, and Air Products operate many of the regulated facilities.

Perhaps the most relevant of TCEQ's programs with regard to hydrogen is the Texas Emission Reduction Plan (TERP). Established in 2001, TERP offers various funding incentives to reduce air pollutants and improve air quality standards under Health and Safety Code Chapters 386-395.[80]

Hydrogen is explicitly mentioned in many of the sub-incentives. In fact, as indicated in Table 7, TERP provides multiple incentives for hydrogen adoption, although they are primarily focused on transportation and re-fueling infrastructure. There is potential complementarity with heavy-duty transportation applications in and around industrial centers and port facilities, as fleet transportation routes for freight can leverage industrial scale hydrogen applications in predictable ways, through logistics planning and management and potential co-location of hydrogen-fueling and freight-loading facilities. If increasing scale is a primary goal, a more effective set of incentives would leverage the comparative advantages that already exist in the state, namely the industrial sector, and focus on promoting competition.

A notable feature of the programs offered through TERP administered by TCEQ is that they tend to focus on stimulating demand by subsidizing end-use infrastructure, which is similar in strategic scope to the suite of policies in California that include the LCFS. This is a critical point in the broader strategic engagement to increase the use of hydrogen in efforts to decarbonize energy systems; namely, one must consider the full value chain, or both supply- and demand-side incentives.

Table 7. Hydrogen Incentives through TERP in Texas

Emissions Reduction Incentive Grants (ERIG) and Rebate Grants Programs, TERP – TCEQ
The ERIG Program provides grants to improve air quality in nonattainment areas and other affected counties. Eligible projects include those that replace, retrofit, repower, or lease/purchase new heavy-duty vehicles, develop alternative fuel dispensing infrastructure and electrification infrastructure, and involve alternative fuel use. The Rebate Grants Program provides grants to upgrade or replace diesel heavy-duty vehicles and non-road equipment.
Clean School Bus Grants, TERP – TCEQ
Any public school district or charter school may receive a grant through TCEQ to pay for incremental costs to replace school buses or install diesel oxidation catalysts, diesel particulate filters, emission-reducing add-on equipment, and other emissions reduction technologies in school buses.
Texas Clean Fleet Program (TCFP), TERP – TCEQ
The TCFP provides grants to fleets to replace existing fleet vehicles with alternative fuel vehicles (AFV) or hybrid electric vehicles (HEV) that reduce emissions of nitrogen oxides or other pollutants by at least 25%. Neighborhood electric vehicles do not qualify. The last grant round was awarded in 2020 to five applicants (three school districts and two transit authorities) with a total of approximately $7.5 million.
Light-Duty Motor Vehicle Purchase or Lease Incentive Program (LDPLIP), TERP – TCEQ
LDPLIP is for the purchase or lease of light-duty vehicles using compressed natural gas or propane (up to $5,000), and hydrogen or electricity (up to $2,500). As of mid-2022, 386 vehicles had been awarded.
Governmental Alternative Fuel Fleet Grant (GAFF) Program, TERP – TCEQ
GAFF covers the purchase or lease of vehicles powered by natural gas, propane, hydrogen, or electricity. Grants are available based on vehicle class, ranging from $15,000 for Class 1 vehicles up to $70,000 for Class 7-8 vehicles. Up to 10% of funds may be for purchase, lease, or installation of refueling infrastructure, or refueling services. $6 million was awarded to a school district in 2021.
New Technology Implementation Grant (NTIG) Program, TERP – TCEQ
The NTIG program provides grants to offset the cost of implementing existing technologies to reduce pollution from stationary sources, including energy storage projects. The program has provided grants for electricity storage, improvements in combustion efficiency, process efficiency, and CO_2 capture. It has attracted comments related to expansion for hydrogen applications.[81]

Sources: Alternative Fuels Data Center, (https://afdc.energy.gov/laws/), U.S. DOE Energy Efficiency and Renewable Energy. See also TCEQ-TERP (https://www.tceq.texas.gov/airquality/terp/programs), Texas Statutes (http://www.statutes.legis.state.tx.us/), Transportation Code, Health and Safety Code, Water Code, and Texas Administrative Code (http://www.sos.state.tx.us/tac/index.shtml).

4. Public Utility Commission of Texas (PUCT)

The PUCT "regulates the state's electric, telecommunication, and water and sewer utilities, implements respective legislation, and offers customer assistance in resolving consumer complaints."[82] It was created in 1975 when the Texas Legislature passed the Public Utilities Regulatory Act. Over time, with legislatively directed shifts in market structure, PUCT has evolved from being chiefly responsible for regulating utility rates to oversight of competitive markets. This evolution has potential bearing for the future of hydrogen, particularly if state oversight of hydrogen markets expands in coming years.

Currently, PUCT has no direct authority over the hydrogen value chain. Additional regulatory guidance is required for PUCT to have authority over the use of hydrogen storage, hydrogen-based load balancing services in power generation (through fuel cells, for example), how hydrogen might be blended into natural gas product streams for shipment on existing pipelines, hydrogen applications in residential and commercial heating, and expanded industrial uses of hydrogen. Notably, as the hydrogen market expands, historical precedent indicates PUCT may eventually take on a market oversight role, similar to its current oversight of telecommunications and electric power markets.

5. Texas Constitution and Statutes[83]

In addition to the measures outlined through TERP with TCEQ, referring to Health and Safety Code Chapters 386, 390-393, and 395 (which establish TERP, the Clean School Bus Program, NTIG, TCFP, and GAFF, respectively), there are specific statutes associated with the Texas Constitution that have bearing for hydrogen. For example,

- Health and Safety Code Chapter 382 (Clean Air Act) recognizes hydrogen as an "advanced clean energy project" fuel source for electricity generation.
- Natural Resources Code Chapter 111 (Common Carriers, Public Utilities, and Common Purchasers) defines common carriers and includes hydrogen and CO_2. As a common carrier, the pipeline operator is granted the power of eminent domain and is obligated to publish tariffs, provide transportation services without discrimination, ensure no discrimination between shippers, and provide equal compensation for like services.
- Natural Resources Code Chapter 118 (Pipeline Assessment and Testing) applies to any pipeline that is in an incorporated or unincorporated city or village, or resides in a residential or commercial area. Given the nature of hydrogen market expansion in industrial applications and connections to producers that are not co-located and/or storage facilities, this chapter is likely to apply.
- Natural Resources Code Chapter 120 (Verification, Monitoring, and Certification of Clean Energy Projects) and Natural Resources Code Chapter 121 (Ownership and Stewardship of Anthropogenic Carbon Dioxide) specifically address CO_2 capture and sequestration. As such, they each have direct bearing on hydrogen production that employs carbon capture technology, such as "blue" hydrogen.
- Natural Resources Code Chapter 211 (Hazardous Liquid Salt Dome Storage Facilities) applies to "any liquid which is not defined as a solid or hazardous waste by Section 361.003, Health and Safety Code, and which is petroleum or any petroleum or liquid natural gas product; or any hydrocarbon in a liquid state, other than liquified natural gas, that has been determined by the United States secretary of transportation to be a hazardous liquid." Hence, hydrogen-derived products such as ammonia and methanol would likely be covered by Chapter 211.
- Tax Code Chapter 11 (Taxable Property and Exemptions) Sec. 11.31 (Pollution Control Property) stipulates that owners of properties used to control air, water, or

land pollution are entitled to property tax exemption. Electricity generated from hydrogen fuel cells is included in the facility list by TCEQ.

- Tax Code Chapter 152 (Taxes on Sale, Rental, and Use of Motor Vehicles) Sec. 152.090 (Certain Hydrogen-Powered Motor Vehicles) Subchapter E (Exemptions) indicates that vehicles powered by hydrogen that meet at least the Phase II standards established by California Air Resources Board for an ultra-low emission vehicle will be exempted from retail sales tax, use tax, and rental tax of motor vehicles.

In sum, there are various provisions in the Texas statutes that further impact various parts of the hydrogen supply chain. Moreover, as interest in hydrogen grows, it is very likely the points of legal, policy, and regulatory intervention will expand. This will be in the interest of market expansion, improved environmental quality, economic growth, and job creation, as well as concerns about safety in the production, transport, storage, and use of hydrogen.

X. Coordination and Accelerating Hydrogen Development

There are multiple technologies for producing hydrogen. Some are less CO_2-intensive than others, some have value propositions for carbon/CO_2 that alter commercial prospects, and some are better suited for specific regional comparative advantages than others. In every case, scaling different hydrogen production technologies brings supply chain challenges that must be overcome for growth to ensue. These include

- infrastructure needs that vary by technology;
- legacy infrastructure footprints — such as existing industrial corridors and backbone transportation networks — that are large in some regions, but non-existent in others;
- differences in land-use needs, types of competing activities, and societal attitudes; and
- policy and regulatory frameworks that may need to adjust to accommodate growth.

Every production process (hydrogen or not) involves a value chain associated with raw material inputs that are used in the production process to deliver a final product, and potentially a co-product, to market. Thus, coordination theory plays a central role in understanding how supply chains develop.[84] Figure 11 highlights a simplified version of a supply chain for a final product with an associated co-product, where value is created along every part of the chain. The realization of value at every link is critical for the commercial prospects of investing in each "link" of the supply chain. If a value proposition cannot be realized at every link, then investment will not occur. In fact, if *any* part of this complex set of interactions breaks down, the commercial viability of investments at *every* link is compromised, and the entire chain will fail to materialize.

Consider, for example, if there are hurdles that prevent investments in “product transport” in Figure 11. This will lead to a situation where the value to “final production” must come entirely from the sales of the “co-product.” If this value is not sufficient to support the commerciality of all investments from “raw material” to “final production,” then no investment will occur anywhere. If a firm decides to invest anyway, it may see the market develop as hurdles are removed, but it exposes itself to significant risk of bankruptcy due to “coordination failure” along the supply chain. Investments at every link in the supply chain are accelerated as the value proposition associated with the “final product” and the “co-product” increases. Thus, measures that enhance value propositions tend to support investment.

Figure 11. Coordination and the Value Chain

Source: Authors.

Supply chain complexities can lead to the “valley of death” for new technologies. Hence, identifying pathways that lower burdens for deployment is critical, and overcoming fixed costs of adoption is core. Imagine, for instance, an example of a lab-developed “widget” production technology that can produce widgets at half the cost of what is currently done commercially. The developers feel they have a strong case to sell their technology as revolutionary for the industry, and it may be. However, when they take their case to the commercial sector, they find interest in the concept, but no buyers. Why? Because their technology requires the development of entirely new supply chains to support its deployment, and those supply chains bear a fixed cost that is too high. Thus, the commercial case for the lab-developed widget technology is not strong enough to ensure cost-effective coordination along a new supply chain, so coordination failure ensues, and the technology falls into the valley of death. In other words, it was not sufficient that they could produce widgets in the lab for half the cost (much less parity); they needed to drive even greater cost reductions to overcome the fixed-cost barriers to support the development and operation of a commercial-scale supply chain to enter the market. It is for this reason that technologies that leverage legacy supply chains (and infrastructures) tend to "build bridges" over the valley of death, thus finding a greater likelihood of success.

Regarding hydrogen market development, some hydrogen production technologies will face fewer and lower barriers to market entry than others in different regions. For example, in regions with a robust natural gas production, transportation and end-use footprint, blue and turquoise hydrogen production technologies can leverage this by making investments along the existing natural gas supply chain. Not only does this simplify the supply chain requirements for greater hydrogen production, it also lowers the cost of shifting to hydrogen. This can encourage greater market participation, which is critical for growth.

Pathways that do not maximize market participation through lower fixed-cost options for integration will find themselves at risk of coordination failure. With limited market participation, deals to support investments along the value chain must be bilateral, requiring identification of a specific counterparty with a specific requirement. Thus, investments are highly conditional on counterparty identification.[85] While this can be necessary for initial investments in a new market that lacks depth and liquidity, it also presents a ceiling on long-term market growth potential.

In the presence of a liquid market hub, investments along the value chain are de-risked because direct counterparty interaction is not needed. This facilitates investment from all players. In the absence of a liquid market hub, investments are limited to parties with sufficient risk tolerance, thereby diminishing the scale of the activity. One can think of this through the lens of real options. Investing in infrastructure is a real option; one only exercises the option when the investment is expected to be profitable. In the absence of market liquidity, a "liquidity premium" exists that renders the option value lower, thus reducing investment. Market liquidity increases scale.

As noted previously, infrastructure is a necessary condition for a market hub to develop. But infrastructure alone is not sufficient. Infrastructure provides a path for producers and consumers to transact. When access to that path is limited, if another supplier wants to bring a production technology into the market, they will be forced to build parallel, redundant supply chain infrastructure to transact with a consumer. Similarly, if a new consumer seeks to purchase hydrogen, but has no (or limited) access to the upstream supply chain, they must identify potential counterparties to sell them hydrogen and develop the infrastructure needed to facilitate the transaction. In either case, the lack of access to existing infrastructure raises the cost to both the supplier and demander.

Policy and regulation that alters the status quo by supporting new infrastructure development and/or altering the rules of market participation (through open access, for example) will be needed to support sustained growth. If open-access regulation, for example, stimulates new supply and/or demand, the need for infrastructure to connect market participants and facilitate transactions will be revealed through price. Transparent price formation brings information to markets that facilitates cost-effective investment, which is why the development of a physically and financially liquid market is of the utmost importance for growth.

An example of coordination at work in an energy setting can be seen in a relatively recent experience in the Texas electricity market. The Texas power generation market has seen incredible expansion of wind generation capacity, and recently solar generation and battery storage capacity. In fact, relative to other states in the U.S., Texas is No. 1 in wind capacity (26% of U.S.), No. 2 in battery capacity (10% of U.S.), and No. 3 in solar capacity (10% of U.S.), which cumulatively makes it No. 1 in the U.S. for total MWs of installed "green" capacity. Texas also has the largest natural gas generation fleet in the U.S., which turns out to be an important balancing factor for grid stabilization.[86]

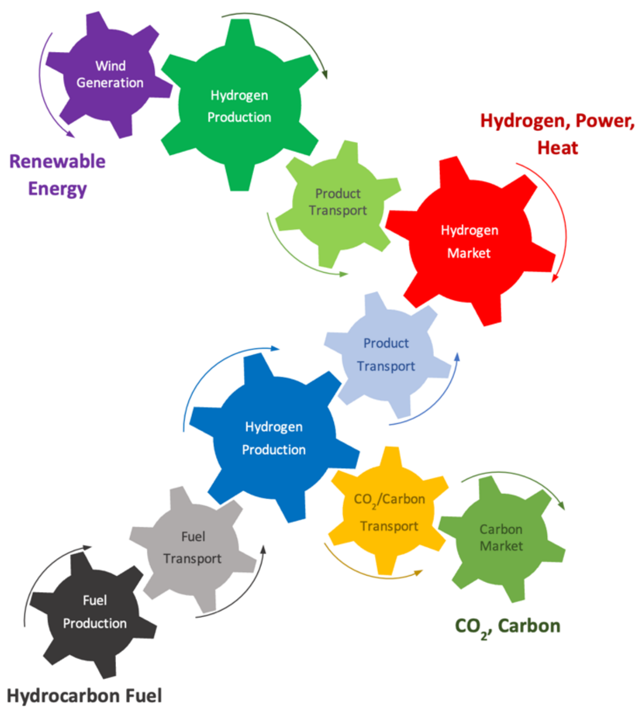
The transformation of the power generation fleet is a culmination of several factors. Consider wind first. There is a lot of privately held land located coincidentally with a robust wind resource in West Texas, which sets the stage for landowners to capitalize on opportunities to capture wind resources for profit. The introduction of government incentives provided an ability to bank a guaranteed payment for generation (through production tax credits for wind) in order to underwrite capacity investments. The result was tremendous expansion of wind generation (in West Texas, initially).

However, wind capacity growth eventually ran into transmission constraints. The federal subsidy support for generation drove an overinvestment in capacity relative to the ability to market the product. This disconnect threatened the entire enterprise with a coordination failure, until the state stepped in to authorize a $7 billion transmission investment through the creation of Competitive Renewable Energy Zones (CREZ). So, the state government effectively underwrote the build-out of the supply chain needed to better integrate wind generation into the Texas power market. The CREZ provided transmission, which allowed access to a liquid market. This de-risked investment in renewable capacity and supported even greater expansion. The end result is the largest wind fleet in the U.S.

Hydrogen markets may follow a similar path. Namely, policy is currently hyper-focused on stimulating the production of hydrogen, largely through loan guarantees, grants, and subsidies, with stimulus for demand coming in a distant second, and storage and commodity transportation a distant third and fourth, respectively. This will tend to yield outcomes that should be expected, where the subsidized parts of the hydrogen supply chain see the greatest amounts of capital investment. In other words, subsidies will drive an allocation of capital into the most heavily subsidized parts of the supply chain.[87] This will eventually yield binding constraints on the unsubsidized parts of the supply chain. If prices are transparent and investment is unimpeded by other policies and/or regulations, then market participants will respond to price dislocations that arise with constraints by investing along the supply chain to capture value. But if transparency is absent, investment is otherwise impeded, and/or hydrogen adoption in end-use is slow to respond, market participants will not see value and therefore will not invest. So, there must be alignment between policy support and market forces, i.e., a full value chain approach.

Consider Figure 12, which is a re-imagined version of Figure 11 specifically for the case of hydrogen. As depicted, two different sources of hydrogen supply can meet market demand. From top to bottom, wind generation provides a renewable source of electricity for electrolyzers to produce hydrogen (green hydrogen). After production, hydrogen must be transported to the market for end-use, so coordination is required from the installation of wind generation capacity to electrolyzer capacity to pipeline capacity to a point of offtake by an end-user.

Figure 12. Coordination and Hydrogen



Source: Authors.

Figure 12 also depicts the capability for hydrogen to be produced using a hydrocarbon feedstock, such as natural gas (grey, blue, or turquoise hydrogen). In the case of grey hydrogen, which is how most hydrogen is currently produced, the supply chains that connect the natural gas wellhead all the way through the hydrogen production facility to an end-user are already well-developed as a matter of legacy. As a result, the opportunity to convert grey to blue or turquoise — thus reducing the carbon intensity of the existing hydrogen supply chain — is a matter of developing supply chains around the co-product (CO_2 or solid carbon, respectively). This is where current policy is already playing a role. Specifically, the expansion of 45Q is meant to stimulate growth in the capture and sequestration of CO_2.

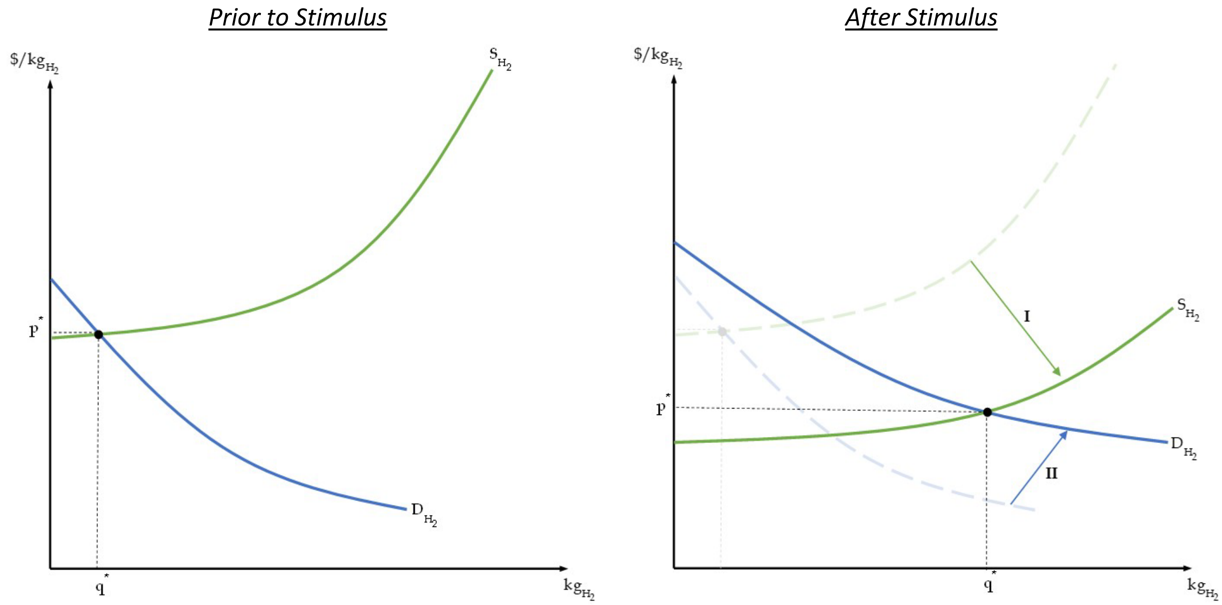
While subsidy support will be effective in many cases, long-term hydrogen market growth would benefit from innovations that reveal a value for CO_2 and/or solid carbon. Consider, for example, a case where advanced materials from solid carbon produced through pyrolysis (turquoise hydrogen) drive a value proposition that dictates expansion of a carbon market that is entirely commercially motivated. Then, it is relatively easy to envision a market where solid carbon as a feedstock for advanced materials applications drives investment in turquoise hydrogen, so much so that the hydrogen is the "by-product" from a commercial standpoint. The Monolith hydrogen facility currently in operation in Nebraska is a prime example. That plant produces turquoise hydrogen and carbon black. The hydrogen must compete in the current market, but the carbon black is also sold as a feedstock for other products such as tires, supporting the commerciality of the entire enterprise. Thus, innovations in material science that drive expanded uses for cost-competitive carbon-based materials could drive a "materials transition" that enables low-carbon energy transitions — with hydrogen playing a major role.[88]

XI. Findings and Recommendations: A Light to Guide the Way

Rather than recommend specific policies and regulatory actions, we take the approach here of providing a framework to evaluate how market interventions can be directed. In the end, it is important to stimulate investments along the *entire* supply chain to support market growth. This will typically happen on its own course with cost reductions, demand growth, and transparent price signals. However, given the policy emphasis on accelerating CO_2 reductions through energy transitions, there are steps that can be taken to stimulate demand, supply, and the infrastructures needed to facilitate transactions.

Figure 13 summarizes, with some degree of generality, the types of measures that can be taken. Each of the indicated measures that shift supply (I) and demand (II) have been discussed throughout. Supply-side shifters, as indicated in Figure 13, can lower cost and make supply more elastic (or flatter). For example, simple subsidies tend to shift the supply curve down by lowering cost. But if subsidies are graduated based on CO_2 intensity, then they can re-order the relative cost of production technologies, thereby flattening the curve. In addition, if market reforms stimulate transparency, the perceived risks of investing in new technologies, rather than incumbent technologies, can be reduced, which also lowers and flattens the curve.

Figure 13. Shifting the Hydrogen Supply-Demand Balance



I: Measures that increase supply and make it more elastic:

- Tax/fiscal policy that lowers infrastructure and project fixed/operating costs. This includes federal measures, such as 45Q and 45V, but local measures, such as grants and tax abatements, matter too.
- Government grants, loan guarantees, and other subsidies to suppliers and shippers.
- Reduce permitting and siting restrictions.
- Reduce market risk by increasing transparency and/or liquidity.
- Market designs/regulatory structures that reduce barriers to entry along the supply chain.
- Innovation, new technologies, and new products (i.e., materials transitions).

II: Measures that increase demand and make it more elastic:

- Consumer preference and ESG-motivated investor sentiments that drive higher returns for low-carbon commercial attributes.
- Government grants, loan guarantees, and other subsidies to end-users.
- Direct government mandate/regulation.
- Reduce market risk by increasing transparency and/or liquidity.
- A price on CO_2.

Source: Authors.

On the demand-side, similar arguments apply. If risk of market entry is reduced through transparency measures, then additional demanders can enter the market at any given price. The degree to which this happens is conditional on other factors, but it tends to increase demand at any given price below the maximum willingness to pay (the point at which demand drops to zero due to alternatives being less costly). If there are direct subsidies to demand, then demand will increase at every price, representing a shift out of the curve.

In the end, there are various measures that can be used to drive the market to a new equilibrium. The indicated shifts in Figure 13 are qualitative. A quantitative assessment is beyond the scope of this exposition, but it is being pursued in further research.

It should be noted Figure 13 is not an indication that a *carte blanche* approach is appropriate. Market interventions through policy action or regulatory shifts should be aligned with comparative advantages. Federal policy and regulation must remain flexible and not "pick winners" if anti-competitive market outcomes are to be avoided. This encompasses measures that, among other things, encourage innovation, provide support through subsidies and grants to encourage demand growth (market-making) and investment in supply chains, and develop regulatory structures that provide clarity and enhance transparency. State and local policy can be crafted in ways that leverage federal policy and play to regional comparative advantages.

Thus, state policy can take a sector-specific focus to leverage legacy infrastructure while providing policy support through measures such as local tax abatement, to the extent the commercial activity that is stimulated will generate regional economic growth.

Fiscal incentives are helpful to stimulate investment, particularly when the commercial prospect is not otherwise sufficient. One motivator for the use of fiscal incentives — such as subsidies, grants, and loan guarantees — is the existence of a "market failure" due to a non-priced externality, such as the environmental costs of hydrocarbon combustion. To be clear, pricing the externality directly (such as a CO_2 tax or some other pricing mechanism) is the first best approach that allows market participants to respond to the pricing signal by internalizing the externality in economic decision-making.[89] But when this is not politically feasible, another option is government support for investments that could displace the source of the externality or support its mitigation. This is where fiscal incentives for alternative technologies — such as those for wind, solar, batteries, carbon capture and sequestration, and hydrogen — come into play.

However, fiscal incentives alone may have limited impact if other issues are not resolved. To successfully achieve the scale needed for broad decarbonization, policies must collectively take a full value chain approach. Barriers to permitting and siting new infrastructure, for example, can prohibit the development of the value chains necessary to meaningfully impact the energy mix. In addition, market structure must promote transparency — in price and volume — to incentivize greater levels of investment. So, the regulatory architecture is also important to achieving scale. In the end, if any such impediments exist, government fiscal incentives will need to increase to overcome the burdens that are present. This could lead to an outcome in which the externality is overpriced and the market outcome is not efficient.[90]

In general, the prospects for growth in hydrogen are regionally differentiated, tied to existing comparative advantages, linked to non-hydrogen supply chains, heavily dependent on coordination, and will need market depth. For Texas, regional comparative advantages are numerous. Texas has tremendous natural resource wealth, ranging from land to wind to sun to geologic conditions that yield ample supplies of natural gas and oil, as well as abundant pore space for CO_2 sequestration and long-term storage of hydrogen. Altogether, this creates opportunities for a number of different hydrogen production technologies in Texas. As a result, upstream resource availability will not be an impediment for efforts to stimulate the deployment of different production technologies. Barriers, should they be present, will be farther downstream.

Another pair of comparative advantages for Texas is its robust industrial sector — especially in petroleum products, chemicals, plastics, and rubber manufacturing (accounting for 13.2% of U.S. GDP from these sectors in 2021) — and access to a tremendous combined port capacity along the Gulf Coast. These are intimately linked because industrial activity in Texas is outward facing through ports, serving other domestic markets as well as international destinations. As a result, the region has the necessary points of leverage to facilitate growth in multiple markets, particularly those that can utilize legacy infrastructure. For instance, Texas has a large natural gas production, transport, storage and end-use footprint (accounting for 60.5% of U.S. GDP in the oil and gas extraction sectors and 24.6% of U.S. GDP in the pipeline transportation sector in 2021), and deep expertise in logistics and supply chain management (accounting for 11.6% of U.S. GDP in the wholesale trade sector and 10.0% of U.S. GDP in the transportation and warehousing sector).[91] Texas is already home to the majority of the necessary U.S. hydrogen supply chain components (and associated infrastructure, including two-thirds of U.S. hydrogen transport infrastructure), so there is a backbone in the region upon which to grow. Currently, this advantages natural gas as a feedstock for low-carbon hydrogen production technologies, but market growth will inevitably open opportunities for other sources of hydrogen, provided the infrastructure is accessible. Green hydrogen, for example, can leverage the massive wind resources that exist in the state, but its longer-term success will hinge on its ability to access the hydrogen market. Hence, to fully leverage the resource wealth and legacy infrastructures in Texas so that value creation can be fully captured, appropriate regulatory designs that ensure competition are very important.

Because Texas has a robust port infrastructure along the Gulf Coast that supports significant domestic and international trade, encouraging competition can yield efficiencies that stimulate market expansion focused on exports of hydrogen and hydrogen-derivatives, to the extent they are cost-competitive.[92] This will, in turn, support market depth and liquidity that reduces risk and facilitates further growth. Regionally, this is critical for long-term economic viability.

It is worth noting the current demand-side focus on providing grants and subsidies for transportation applications, but this may not be the path (for light-duty vehicles in particular) that promises the greatest potential for growth. Our survey results indicate it is, at best, a long-term opportunity. This is particularly apparent when considering the recent growth of EVs. EV purchases have received strong subsidy support. In addition, the ability to recharge at home as well as at the office and commercial establishments reduces a significant barrier to adoption. If refueling (recharging) was compromised by a lack of available locations, EV adoption would be much slower. This is yet another example of a coordination problem. Recharging infrastructure for EVs (to date) has leveraged existing electricity distribution networks. However, for light-duty hydrogen FCEVs, refueling infrastructure must be installed as an entirely greenfield venture. This raises the cost of adoption. Even in California, where a program to expand hydrogen refueling is underway, EV adoption has exceeded that of all other alternative fuel light-duty vehicles.

There are opportunities to use public funds to support grants and subsidies to promote hydrogen market expansion. Using TERP is one path to promoting deployment of new production technologies, end-uses, and infrastructures. Consideration should therefore be given to expanding the eligibility of hydrogen for existing TERP incentives, as they could trigger additional investments. But TERP is not a panacea.

Other potential areas where policy and regulation can help include things such as

- modifying electricity market rules to compensate reliability services that all forms of energy storage can provide;
- establishing/adopting a certification program for "clean" hydrogen that includes a fair and detailed CO_2-intensity scoring along the supply chain to accurately account for and incentivize hydrogen technologies and pathways with the most significant emissions reduction impact;[93]
- establishing a regulatory framework that promotes competition for capacity rights in pipelines and storage;
- streamlining permitting for hydrogen projects and related supply chain infrastructures;
- encouraging pilot and demonstration projects to learn where economies of scale and other cost-saving gains can be made; and
- adopting transparency measures that establish frequent reporting mechanisms for hydrogen storage and allow for better accounting of demand (for example, in the Monthly Report and Operations Statement for Refineries, separating hydrogen from "miscellaneous" would allow a more accurate assessment of current consumption levels[94]).

In Texas, focusing on the conversion of current industrial uses of hydrogen to low-carbon production technologies is likely the most expedient path to broader use of hydrogen. Then, to the extent that heavy-duty transportation applications and other new or emerging uses can benefit from the build-out of the large, backbone infrastructures needed for industrial-scale applications, the opportunity for market growth and the development of physical and financial hubs is enhanced.

The role of hydrogen in the U.S. energy system is on the precipice of significant growth, and it is likely that different regions will leverage different technologies, policies, and commercial approaches in attempts to expand the hydrogen market. However, it remains to be seen how the industry will handle commercial and legal challenges related to hydrogen infrastructure expansion. This is important because, just as with natural gas, more hydrogen infrastructure will allow regional trade and enable the development of an efficient *national* hydrogen market. Accordingly, this may foretell a future role for federal policy.

In the end, low-carbon hydrogen market development is a massive coordination problem. Successful growth will require thoughtful policy and regulatory intervention that leverages regional comparative advantages, promotes competition, and removes barriers to infrastructure development and market entry. Texas is in a very advantageous position to play a leading role in driving broader hydrogen adoption and market growth, but the script is still being written.

XII. Endnotes

1 Although hydrogen is commonly noted as an energy "source" it is better referenced as an energy "carrier" because it must be produced using other sources of primary energy (such as natural gas) and secondary energy (such as electricity).

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[83] Texas Constitution and Statutes, https://statutes.capitol.texas.gov/.

[84] The Prisoner's Dilemma is the simplest example of coordination theory. In that case, two thieves, who are questioned by police based on circumstantial evidence, "rat" each other out rather than coordinate on their story. This leads to them both going to prison, rather than walking away free. Hence, coordination failure occurs because their inability to coordinate led to the worst possible outcome, for them.

[85] This is related to search and matching theory and rigidities in adjustment in economics. Search and matching theory is typically applied to labor markets to describe observed frictions in unemployment data relative to economic output. In the presence of rigidities, the adjustment is slowed. (See, for instance, Carlos Thomas, "Search Frictions, Real Rigidities, and Inflation Dynamics," *Journal of Money, Credit and Banking* 43, no. 6 (2011): 1131–64, https://www.jstor.org/stable/20870109).

[86] See https://www.bakerinstitute.org/electricity-texas for more on this topic.

[87] This is not necessarily economically inefficient. That depends, in large part, on whether the subsidy is offsetting an externality that is driving a deviation from a socially efficient allocation in the first place.

[88] The Carbon Hub at Rice University is an example of where innovations in material science seek to reduce costs for carbon-based materials, thus supporting a materials transition. See https://carbonhub.rice.edu/.

[89] For a discussion of various CO_2 pricing mechanisms, see, for example, Joseph E. Aldy and Robert N. Stavins, "The Promise and Problems of Pricing Carbon: Theory and Experience," *The Journal of Environment & Development* 21, no. 2 (2012): 152–180, https://doi.org/10.1177/1070496512442508. For a discussion of the impact of CO_2 pricing on national-level emissions, see Rohan Best, Paul J. Burke, and Frank Jotzo, "Carbon Pricing Efficacy: Cross-Country Evidence," *Environmental and Resource Economics* 77, (2020): 69–94, https://doi.org/10.1007/s10640-020-00436-x.

[90] There is an extensive body of literature full of debate over the economically efficient treatment of externalities that is beyond the scope of this paper. Some of the most relevant references are A. C. Pigou, *The Economics of Welfare*, 2nd ed, Macmillan (1924); Ronald H. Coase, "The Problem of Social Cost," *Journal of Law and Economics* 3 (1960): 1-44; and William J. Baumol, "On Taxation and the Control of Externalities," *The American Economic Review* 62, no. 3 (1972): 307–22. The literature spawned by these papers is enormous.

[91] Data on U.S. GDP are derived from data for GDP by state and by industry from the U.S. Bureau of Economic Analysis (see apps.bea.gov/regional/downloadzip.cfm).

[92] Note, export of hydrogen and/or hydrogen-derivatives is not necessarily the most cost-competitive option. For example, LNG exports through existing facilities can provide natural gas feedstocks all

over the world. If importers of U.S. LNG prefer hydrogen, they may opt to convert the natural gas to hydrogen at the tailgate of the regasification facility, and market the hydrogen domestically. This requires additional investment in the CO_2/carbon market infrastructure, which can take various forms, but it also leverages existing LNG and natural gas infrastructure. So, the fixed costs of converting an entire supply chain from natural gas to hydrogen will matter.

[93] To realistically assess the environmental impact, measurement and reporting on leakage rates along hydrogen supply chains, including methane, is critical. Capturing and sharing such data is a transparency measure that is particularly critical for effective mitigation for the development of a hydrogen economy in the long term. The Texas Gulf Coast is an ideal testbed given the existing hydrogen supply chain and supporting infrastructure.

[94] RRC, "Monthly Report and Operations Statement for Refineries," April 3, 2021, https://www.rrc.texas.gov/media/i3dfsbfq/2021-april-03-0031.pdf.