Chapter 3

LCI HYDROGEN—CONNECTING INFRASTRUCTURE

I. OVERVIEW

The development of a low carbon intensity hydrogen (LCI H_2) infrastructure emerges as a critical enabler for the United States to achieve its energy security, competitiveness, and ambitious decarbonization goals. Recognizing the diverse and dispersed nature of hydrogen supply and demand across the United States, this chapter outlines the necessity for an integrated, safe, flexible, and scalable infrastructure that can meet energy resiliency needs. It emphasizes the integration of various transportation, storage, and delivery mechanisms, tailored to regional supply-demand dynamics, and supported by technoeconomic analyses. This infrastructure is pivotal for bridging the gap between current capacities and the projected demand of 75 million metric tons per annum (MMTpa) by 2050 under a net zero scenario.

Addressing the current state of hydrogen infrastructure in the United States, which is primarily concentrated in the Gulf Coast states and California, the chapter identifies significant expansion opportunities beyond those regions. It also highlights the importance of leveraging existing energy networks and developing new pathways—including the strategic role of hydrogen hubs and export-import infrastructure—to facilitate the transition to a low-carbon economy. The economic considerations underscore the necessity for substantial investments, with a focus on cost-effective solutions, such as pipelines and geological storage for large-scale hydrogen movement and storage.

The chapter further explores the critical role of policy support, public-private partnerships, and technological innovation in overcoming barriers to infrastructure development. It calls for streamlined permitting processes, financial incentives, and market certainty to accelerate the deployment of an integrated, scalable LCI H_2 network. The establishment of a robust LCI H_2 infrastructure would support a transformational shift, essential for connecting geographically dispersed LCI H_2 producers with demand centers, thus ensuring a sustainable, competitive, and low-carbon hydrogen economy.

In conclusion, this chapter presents a strategic roadmap for the United States to lead in developing a comprehensive LCI H_2 infrastructure, crucial for meeting its decarbonization objectives. By addressing the technical, economic, and policy challenges of developing that infrastructure, the chapter lays out a vision for a sustainable hydrogen future that emphasizes the infrastructure's role in enhancing energy security and reducing greenhouse gas emissions, thereby positioning the United States as a leader in the energy transition.

II. INSIGHTS

Safe, integrated, flexible, scalable, and resilient LCI H_2[1] infrastructure to connect future supply and demand requirements is needed to unlock U.S. hydrogen competitiveness, attractiveness, and energy security (Figure 3-1). That infrastructure will also help meet U.S. emissions reduction goals. These goals can be advanced by the development of a diverse portfolio of LCI H_2 infrastructure

1 This study defines low carbon intensity hydrogen or hydrogen as it is also defined in the Inflation Reduction Act (IRA) and represented as clean hydrogen (see 2022 IRA; Section 45V(c)(2)).

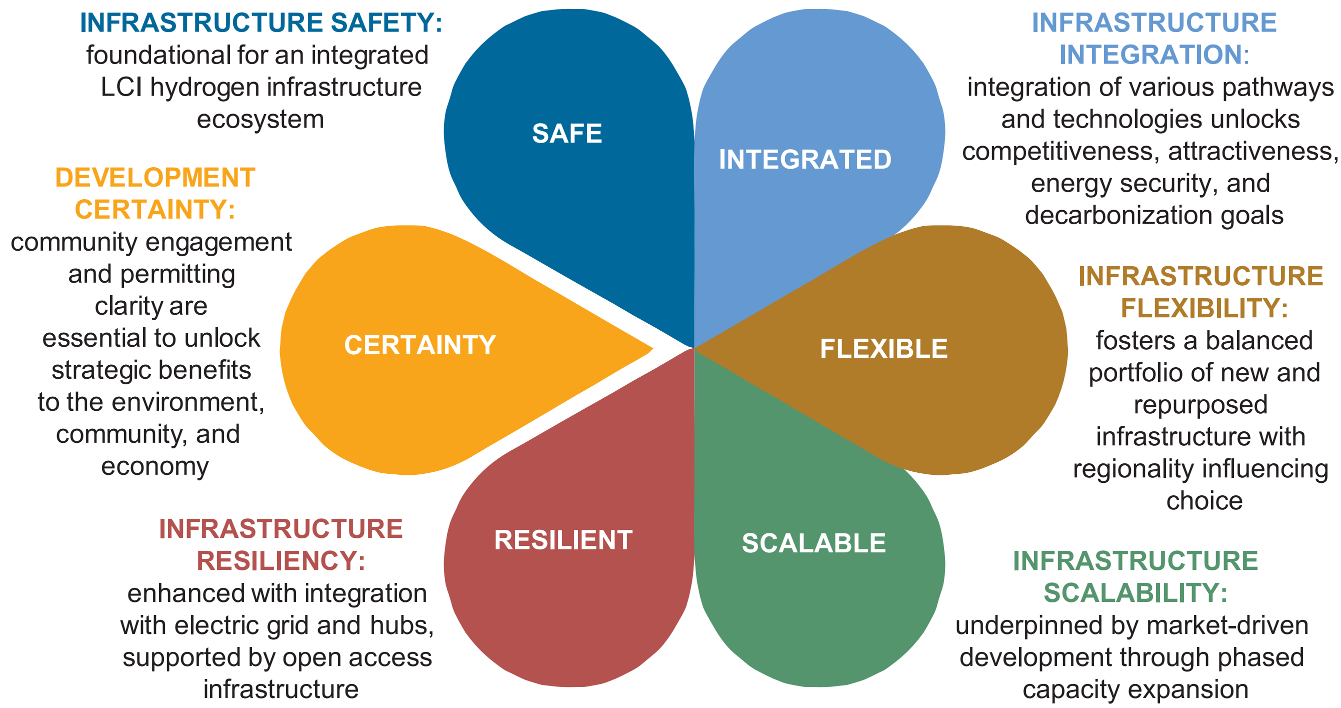


Figure 3-1. *Core Architecture Attributes for LCI Hydrogen Infrastructure Development*

pathways for transporting, storing, and delivering LCI H_2 and associated carbon management technologies—including CO_2 storage infrastructure. Those LCI H_2 infrastructure pathways can connect geographically dispersed LCI H_2 producers with regionally situated LCI H_2 demand centers (each with varying demand needs) across multiple end uses in the United States. There is no single hydrogen infrastructure solution to satisfy every production facility, distance/volume transported, and all the various end-use requirements. As such, the choice of a particular LCI H_2 transportation, storage, and delivery alternative is driven mostly by technoeconomics and regional parameters, with federal, regional, state, and local decarbonization policies underpinning the adoption.

A mature hydrogen transportation, storage, and delivery network currently operates in the United States, delivering feedstock primarily to the refining, petrochemical, and transportation sectors. However, this network is concentrated in the U.S. Gulf Coast and parts of California and is supplied almost exclusively with unabated hydrogen. Merchant producers currently use one of three transportation modes to reach industrial end users: 1) compressed gas through pipelines; 2) truck deliveries of gaseous hydrogen in tube trailers; and 3) truck delivery of liquid hydrogen using cryogenic trailers.

The existing hydrogen infrastructure in the United States serves approximately 11 MMTpa of unabated hydrogen demand. Infrastructure capacity expansion will have significant implications for the growth and development of the hydrogen economy in the United States, as well as for the global energy ecosystem. To meet the 75 MMTpa of U.S. LCI H_2 demand by 2050[2] under a Net Zero by 2050 (NZ2050) scenario would require an optimal capacity mix of connecting infrastructure that is capable of transporting, storing, and delivering LCI H_2 to meet the varying regional supply and demand needs and to enhance overall system flexibility. Market certainty of supply and demand, along with rapid expansion of LCI H_2 infrastructure, is a necessity to enable the emergence of an integrated LCI H_2 infrastructure at-scale by 2050.

Multiple transportation, storage, and delivery pathways are viable with varying technoeconomic

2 Value as predicted by the 2023 MIT economic modeling effort sponsored by the NPC to support this report preparation.

and regional benefits to deliver LCI H_2 at-scale. Key parameters that define or dictate the role of transportation pathways include volume of hydrogen being transported, transporting distance, end-use requirements, and regional constraints. Various modes of transportation and storage options are currently feasible (see Section IV of this chapter for additional information). The economics of transporting LCI H_2 can significantly influence the growth and viability of the hydrogen economy. The development of hydrogen infrastructure, including pipelines, storage facilities, and distribution networks, requires significant upfront investments. The scale of infrastructure development can impact the overall cost effectiveness of hydrogen as an energy carrier. Over the long term, as the market matures with technological advancements coupled with supportive infrastructure policies, economies of scale can lead to potential cost reductions across the various pathways to transport, store, and deliver hydrogen.

As illustrated in Section V of this chapter, high-capacity pipelines delivering large volumes of hydrogen currently offer the cheapest way to move it over longer distances and offers the potential to connect geographically separated supply and demand centers. Leveraging low-cost geologic salt cavern storage in certain regions (e.g., Gulf Coast) with pipeline infrastructure, it is expected that the levelized cost of transportation and storage of large volumes of hydrogen could be $1/kg or less by 2030. The Northwest region, lacking salt cavern storage resources and relying primarily on expensive liquefied storage, is expected to see the levelized cost higher than $1/kg.

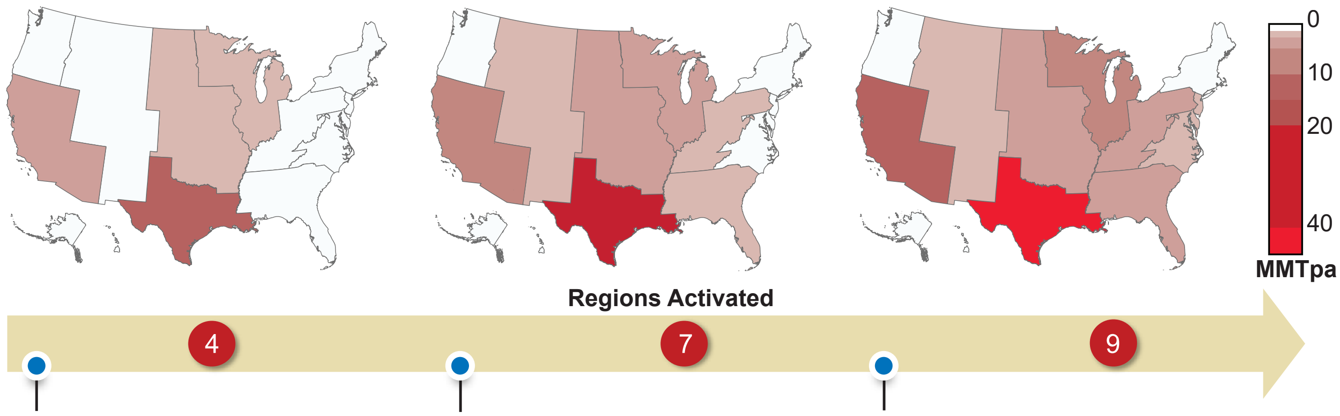
Trucks can be a versatile option for transporting low volumes of LCI H_2 but can be costly. The cost of trucking, including associated infrastructure (terminaling[3] with refueling infrastructure when fuel cell vehicles are the end use) is expected to range from approximately $2 to $3/kg assuming full utilization of assets (see Section V of this chapter for additional information).

The Modeling analysis conducted for this study for the Gulf Coast, the West, and the Great Lakes regions demonstrates that LCI feedstocks for LCI H_2 production are not always located adjacent to demand centers. As a result, significant infrastructure development will be required to connect supply and demand. See Chapter 4: Integrated Supply Chain, which highlights the key factors driving the infrastructure cost variability and influencing the delivered Levelized Cost of Hydrogen across these regions.

Supporting the development of diverse LCI H_2 transportation, storage, and delivery pathways and fostering the evolution of a robust commercial and financially attractive investment market is key to supporting and enabling infrastructure capacity expansion. The accelerated deployment of LCI H_2 will benefit from the implementation of consistent and coherent long-term policies, the holistic evaluation of societal impacts and community engagement practices, targets to close technological gaps, and strategic long-term development plans. LCI H_2 infrastructure scaling and expansion, under an accelerated scenario to meet carbon neutrality goals in the United States by 2050, could take place in three illustrative phases as shown in Figure 3-2. Those phases are characterized by initial activation to trigger LCI H_2 usage, subsequent expansion to meet new end users of LCI H_2, and at-scale market development for economy-wide deployment. Realization of LCI H_2 deployment across all the three phases will require certain milestones to be reached across the infrastructure value chain enabled by supporting policies at both federal and state levels.

Activation phase: Accelerated by the Inflation Reduction Act (IRA), hydrogen tax credits for production (45V), storage (Investment Tax Credits), permanent CO_2 storage (45Q), and the Infrastructure Investment and Jobs Act (IIJA) funding opportunities, along with a streamlined permitting process, the shift to LCI H_2 will primarily occur where supply and demand are colocated, and it will utilize preexisting and new hydrogen infrastructure to support regional pockets of industrial demand centers. Existing hydrogen infrastructure in the United States that currently supports approximately 11 MMTpa demand will serve as part of the foundational infrastructure to support LCI H_2 demand and offers immediate low-carbon energy transition

3 In this context, "terminaling" refers to the facilities needed to either compress and load gaseous hydrogen into trucks, or to liquify and load liquid hydrogen into trucks.



- Well-functioning infrastructure permitting framework
- Transition of existing infrastructure from unabated to LCI hydrogen
- Colocation of supply and demand

- Expansion of infrastructure capacity to serve expanding demand
- Development of intrastate and interstate pipeline infrastructure
- Development of high-capacity long-duration storage (e.g., geological storage)

- Integrated hydrogen transportation and storage network
- Long-duration hydrogen storage supports electric grid reliability and resilience
- Transportation and storage network integrated with export via shipping

ACTIVATION 1 → **EXPANSION 2** → **AT-SCALE 3** →

Note: LCI hydrogen infrastructure capacity expansion will have significant implications not just for the growth and development of the hydrogen economy in the United States but also for the global energy ecosystem.

Figure 3-2. *Infrastructure Capacity of the U.S. LCI Hydrogen Economy*

opportunities and decarbonizing potential for fuel systems in the hard-to-decarbonize industrial sector, including petroleum refining and ammonia production.

Driven by IIJA and IRA, the development of LCI H_2 hubs around industrial clusters and ports will likely begin during the Activation phase. The federal incentives act as seed funding during this phase to enable the hubs to serve as anchors for expansion of LCI H_2 infrastructure to meet new sectoral demand, such as medium and heavy-duty transport. LCI H_2 demand for the transportation sector outside of localized hub clusters may be supported through the development of distributed LCI H_2 production, transport, storage, and delivery infrastructure based on technoeconomic criteria or transported from localized hub regions to meet specific end-use demands.

With expedited permitting for Class VI injection wells, planning and commercial development of new CO_2 pipelines and permanent regional CO_2 storage infrastructure should start to develop to capture, transport, and store CO_2 from new and existing reforming-based hydrogen production facilities.

During the Activation phase, pilot projects and demonstrations as part of Research Development and Demonstrations (RD&D) activities involving hydrogen blending and repurposing (conversion) of existing natural gas pipelines and other supporting infrastructure could occur to enable its deployment during the Expansion and At-Scale phases. During this phase, comprehensively evaluating the feasibility of supporting metallurgical and infrastructure integrity, end-use compatibility, and conversion of existing infrastructure is required while fully addressing safety, reliability, and environmental/community impacts.

Expansion phase: Driven by economies of scale and continued investments in RD&D in the Activation phase, increased demand will drive further expansion of infrastructure capacities to support decarbonization of industrial heat and development of fueling networks along major distribution routes for heavy-duty trucking, etc. As regionally dispersed LCI H_2 hubs begin to establish themselves to serve multiple demand sectors, the development of intrastate and/or interstate regional pipelines connecting more producers and off-takers to synchronize the growth in LCI H_2 supply and demand will be required. With a clear, durable, and expedited infrastructure permitting framework, the planning and development of unbundled, open-access LCI H_2 pipelines coexisting with the current hydrogen business model not under Federal Energy Regulatory Commission (FERC) regulation[4] and regional LCI H_2 storage facilities may start to develop to support increased end-use demand sectors. This will also connect a large diversity of LCI H_2 suppliers utilizing either distributed or centralized LCI H_2 production facilities dispersed far away from demand centers. In addition to the development of new infrastructure, hydrogen blending, and repurposing of existing energy infrastructure may emerge as an effective expansion strategy to leverage the existing rights of way and benefit from lower incremental costs and reduced socioeconomic and environmental impacts.

The growth in regional LCI H_2 demand and supply may drive the need for higher capacity and longer duration energy storage infrastructure—such as liquid LCI H_2 storage facilities, large-scale geologic salt caverns, ammonia, and methanol carrier storage facilities for potential exports of LCI H_2. The development of long-duration hydrogen energy storage infrastructure will also support energy resilience events in regions with interconnected hydrogen hubs and high renewable penetrations, offering frequent low or negative costs of electricity for LCI H_2 production from dispersed hydrogen producers.

LCI H_2 infrastructure planning during this phase should anticipate a range of hub development pathways driven by scale, commercial interests, and various hub archetypes driven by regional/state/local clean energy policies in the United States. Critical LCI H_2 infrastructure elements—such as large-scale regional hydrogen storage resources (salt caverns) or large-scale hydrogen transmission or trunk lines—could serve as the foundation for development and integration of multiple hubs.

Hydrogen storage technologies are at different levels of technological maturity and commercial readiness and the roll out of diverse storage resources, including underground geologic storage, could emerge as the market expands. Geologic storage of hydrogen, which offers larger storage capacities and is less expensive per unit of hydrogen stored (see Section V of this chapter for additional information), tends to require longer development lead times than aboveground storage infrastructure and will need to be planned to ensure the required storage capacity is readily available to meet demand during the Expansion phase. The economic advantage of underground storage is such that within the continental United States, it is preferable, at least on a purely levelized cost basis, to link regions with underground storage to other parts of the country via high-capacity pipelines in most cases.

During the Expansion phase, some gas utilities may elect to evaluate and upgrade certain portions of the natural gas transmission and distribution infrastructure (based on the system integrity evaluation in the Activation phase) to support hydrogen blending into the natural gas system based on customer demand or needs.

Additional growth and capacity expansion of regional CO_2 pipelines and storage facilities needs to occur during the Expansion phase to capture, transport, and store CO_2 from large-scale centralized steam methane reforming (SMR)/autothermal reforming (ATR) hydrogen production facilities to produce LCI H_2.

At-Scale phase: An integrated and mature LCI H_2 transportation, storage, and delivery infrastructure becomes established in the At-Scale phase, unlocking LCI H_2's long-term potential in meeting the U.S. decarbonization goals. As the electric grid moves toward full decarbonization (driven by incentives, scaling, and favorable

4 Future regulatory framework should address potential siting bottlenecks by creating a mechanism to provide federal eminent domain authority for interstate hydrogen pipelines deemed in the public interest, while maintaining the option for continued development of pipelines where operators comply with local and state permitting requirements but do not leverage federal eminent domain. The future regulatory design should consider honoring the current business model of allowing hydrogen systems (not under FERC regulation) that do not seek federal eminent domain rights to remain exempt from any FERC regulation. See Chapter 6: Policy for key actionable enablers addressing unblended interstate hydrogen pipeline authority.

economics), its integration with the LCI H_2 infrastructure offers synergistic (bidirectional and versatile) benefits, including long-duration hydrogen storage, which in turn supports electric grid reliability and resilience.

As innovation and RD&D efforts reduce technology complexity and costs, while also increasing energy storage and efficiency benefits, new emerging hydrogen carrier alternatives may start to be widely used. This may include hydrogen carriers—e.g., ammonia, methanol, liquid organic hydrogen carriers (LOHCs), and solid-state storage technologies such as metal hydrides. A mature market with a national LCI H_2 transportation system could expand to support international trade flows via large hydrogen carrier tanker ships for trading through long-term international offtake auctions/export contracts. Infrastructure development for LCI H_2 export markets will be largely focused in or near the deep-water ports to support international trade flows.

As illustrated previously, it is evident that the LCI H_2 transportation, storage, and delivery infrastructure development across all three phases will act as a critical enabler in integrating diverse and dispersed LCI H_2 production with a broad array of end-use applications at-scale.

Carbon management solutions such as Carbon Capture and Storage (CCS), as well as other auxiliary support infrastructure, will be required to support the development of an integrated LCI H_2 ecosystem. This includes access to water and land/rights of way, proximity to electric and natural gas networks, balance of plant facilities, and associated export infrastructure to support the development of a global hydrogen trade network.

Without the integration of the electric grid and the LCI H_2 infrastructure, the potential synergistic infrastructure benefits will be jeopardized, including the ability for LCI H_2 to support electric grid reliability and resiliency, as well as production of renewable electrolytic hydrogen. The synergistic benefits between the electric grid and the LCI H_2 infrastructure will also dictate the choice of moving energy either as molecules (hydrogen) or as electrons (electricity). Those choices will be driven by several factors, including regional constraints, siting/land-use restrictions, environmental impacts, technoeconomics, and the transporting distance (see Section V.B.4 of this chapter for additional information). Further analysis would be needed to help understand how electricity and LCI H_2 infrastructures can collaborate to create the most value for end users, and how market design and policies can enable the choice.

A. Key Findings

Fostering support for large-scale commercial infrastructure development through public-private partnerships will help accelerate the expansion of LCI H_2 infrastructure to connect supply and demand. Several challenges to the acceleration of development and expansion in the United States must be overcome. Overcoming those challenges involves creating a market with supply and demand certainty (including demand incentives); attracting investments and mitigating financial risks; addressing socioeconomic, community, and environmental impacts; providing the right policy, regulatory, and commercial frameworks for development; promoting market development and expansion attractiveness to developers; and addressing the future implications of hydrogen infrastructure transition to the existing energy labor force. This includes assessing the potential displacement of the existing energy labor force, shifting skills sets, and training requirements to effectively leverage the existing force talent across natural gas, electric, and liquid fuels market.

As illustrated in Figure 3-3, the following key findings can help enable policy and regulatory recommendations to help drive commercial development and scaling of LCI H_2 transportation, storage, and delivery infrastructure in an expeditious manner.

FINDING: Administrative and legal complexity for interstate pipeline development across multiple jurisdictions in the current permitting process could delay development and deployment of necessary infrastructure.

Development of a durable and timely permitting process across all aspects of LCI H_2 transportation, storage, and delivery is essential, given the long lead times and required customization

Figure 3-3. *Key Findings Driving LCI Hydrogen Infrastructure Development*

for each region's infrastructure. Streamlining criteria for project evaluations across federal, state, and local authorities will mitigate conflicting regulatory guidance. Permitting constraints (including siting/right-of-way restrictions) could negatively impact the speed of LCI H_2 and its supporting infrastructure development (interstate pipelines, geologic hydrogen storage, CO_2 transportation and storage, etc.) in the United States. Scaling infrastructure projects is at risk, because they often require streamlined permitting and timely project execution across multiple jurisdictions. Approved interstate and intrastate permits are subject to litigation after approval, with few limitations on ability to file suit. If left unaddressed, this type of litigation could potentially derail the development and scaling of the necessary infrastructure required to support the U.S. decarbonization goals. Strengthening outreach, education, and public engagement should be an essential part of an inclusive permitting process to support LCI H_2 development at-scale. See Chapter 6: Policy for key actionable enablers addressing a streamlined permitting process framework.

FINDING: Additional policies will be needed to incentivize demand for LCI H_2.

For developers and market participants of LCI H_2, uncertainty about future demand is a major impediment to the development and scaling-up of LCI H_2 infrastructure. Without durable policies, the ability to attract market participants and investments for LCI H_2 infrastructure development will be challenged. The administration should work with Congress to establish a national, economy-wide price on carbon that is market-based, technology neutral, transparent, and durable. In lieu of an economy-wide price on greenhouse gas emissions (GHG), which is the preferred approach, well-designed sector policies should be applied (see Chapter 5: Demand and Chapter 6: Policy of this study for additional information), including a national, low-carbon standard for all forms of transportation and a national low-carbon standard to reduce the carbon intensity of the industrial sector. This creates a certainty of demand for LCI H_2, thus encouraging investments in LCI H_2 infrastructure development.

FINDING: **In addition to demand-side incentives, infrastructure-focused incentives to support the development of transportation, storage, and delivery infrastructure help to offset high costs, while also attracting private investments.**

Currently, the IRA incentives are primarily aimed at LCI H_2 production. Subsidies or grants can be used to fund large-scale LCI H_2 transportation, storage, and delivery networks. Strategically designed financial incentives, like the Carbon Dioxide Transportation Infrastructure Finance and Innovation Act (CIFIA) program, can help offset the high costs, making LCI H_2 infrastructure more economically viable for private investments. See Chapter 6: Policy for key actionable enablers addressing a streamlined permitting process framework.

FINDING: **Research and development is needed to quickly commercialize sensor and control equipment capable of detecting, measuring, and mitigating hydrogen fugitive emissions with high precision and frequency.**

Leakage from LCI H_2 transportation, storage, and delivery infrastructure must be minimized to ensure safety and that environmental impacts are mitigated. However, emissions rates across the hydrogen value chain are still highly uncertain due to limited monitoring requirements and high precision measurement technology. Development and deployment of monitoring technologies and practices to minimize hydrogen leakage across the entire value chain (source-to-end usage) is a priority. Hydrogen emissions from real-world facilities must be quantified with empirical measurements. Whereas assessment of emissions rates by an operator with access to hydrogen facilities (production, storage, and end use) can be accomplished with less sensitive, albeit not-yet-commercially-available equipment, learnings from over a decade of research with methane emissions measurement suggest that hydrogen emissions quantification, based on fence line measurements or for wide-area assessments (e.g., pipelines), would likely require hydrogen sensors that are fast (respond in a few seconds) and sensitive (precision at a low parts-per-billion level). Additional research on improved hydrogen leakage detection accuracy and monitoring, including pilot demonstrations, can help test and validate rates, facilitate development of leak detection and prevention technologies, and test emergency response procedures and protocols. Development, operations, and maintenance of hydrogen infrastructure, as well as regulatory frameworks, must seek to minimize leakage to ensure safety and reduce emissions. See Chapter 6: Policy and Chapter 7: Societal Considerations, Impacts, and Safety for key actionable enablers addressing fugitive emissions across the LCI H_2 value chain.

FINDING: **Reaching the Expansion and At-Scale phases of LCI H_2 deployment will require construction of interstate hydrogen pipelines to cost-effectively move LCI hydrogen from supply to demand centers and will require timely permitting and approvals.**

Promoting regulatory certainty by establishing an unblended federal LCI H_2 interstate pipeline framework in the Activation phase is essential. This framework could promote open-access and allow for application of federal eminent domain authority to enable construction of large-scale interstate hydrogen pipelines. As discussed in the Department of Energy's (DOE) Pathways to Commercial Liftoff report,[5] open-access transportation, and storage infrastructure will be helpful in supporting the success of large-scale regional LCI H_2 hubs, where a large diversity of hydrogen suppliers is a key characteristic. A future regulatory framework should honor the current hydrogen pipeline business model by allowing hydrogen systems (not under FERC regulation) that do not seek federal eminent domain rights to remain exempt from any FERC regulation. See Chapter 6: Policy for key actionable enablers addressing unblended interstate hydrogen pipeline authority.

FINDING: **As compared to building entirely new LCI H_2 infrastructure, repurposing**

5 DOE. 2023. "Pathways to Commercial Liftoff: Clean Hydrogen." https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-Clean-H_2-vPUB.pdf.

existing infrastructure to dedicated LCI H_2 service or, in some cases, blending LCI H_2 into existing natural gas infrastructure may provide opportunities for cost savings and more rapid and flexible LCI H_2 deployment. Technical feasibility, end-use demand, and potential environmental/community impacts will all need to be evaluated prior to blending or repurposing.

Collaboration between industry, DOE, Pipeline and Hazardous Materials Safety Administration (PHMSA) and other research institutions is needed to develop best practices, technical standards, and guidelines for blending and repurposing. It should be reinforced that no volume of hydrogen should be blended into existing infrastructure prior to completing a comprehensive assessment to verify the ability to transport hydrogen safely and reliably. See Section VII.B of this chapter for additional information on blending and repurposing.

FINDING: To support an efficient, resilient, secure, and cost-effective hydrogen economy in the long run, it is necessary to evaluate the establishment of Strategic Hydrogen Reserves (SHR) to prevent potential supply disruptions.

An at-scale LCI H_2 economy supporting global hydrogen trade flows could necessitate the development of a strategic hydrogen energy storage reserve (akin to the strategic petroleum reserve) in the future. That hydrogen energy storage reserve could support energy security, resiliency, and supply, while mitigating potential geopolitical supply-demand constraints, cybersecurity risks, and climate-related events. See Chapter 6: Policy for key actionable enablers addressing SHR.

FINDING: It is essential to streamline CO_2 regulatory processes, establish clear guidelines and standards, enhance stakeholder engagement, and provide regulatory certainty regarding approval timeframes.

Currently, the lengthy backlog of carbon storage permit applications for Class VI injection wells in the approval queue at the Environmental Protection Agency (EPA) has weighed down the progress of additional carbon management projects. Expedited timeframes for review and approval of these Class VI well applications will enable development of carbon capture and storage (CCS) projects needed to meet decarbonization objectives. CCS pipeline projects in several states have also encountered delays in securing siting approvals. See Chapter: 6 Policy for key actionable enablers addressing CO_2 transport and storage.

Without addressing the technology, policy, and regulatory enablers as recommended, commercial interest and investments in LCI H_2 infrastructure development could face uphill challenges. Promptly addressing them will help mitigate commercial risks and bring the needed private investments to help scale LCI H_2 infrastructure in a timely manner and to meet the U.S. decarbonization objectives by 2050. The U.S. energy industry has the expertise, capability, and resources needed to partner with governments and stakeholders to expand the current LCI H_2 infrastructure to meet the future supply and demand needs in a new hydrogen economy.

III. WHY TRANSPORT, STORE, AND DELIVER LCI HYDROGEN?

A. Introduction

A highly integrated LCI H_2 transportation, storage, and delivery infrastructure in the United States will be critical to unlocking hydrogen's strategic benefits and meeting the U.S. decarbonization goals in a safe and efficient manner. Safety, along with energy reliability and resiliency, will underpin all aspects of an integrated LCI H_2 infrastructure ecosystem, ensuring that a vibrant low-carbon economy develops based on safe transportation, storage, and delivery practices.

Commercializing an at-scale LCI H_2 economy and meeting the U.S. decarbonization goals by 2050 requires the development of a safe, integrated, flexible, scalable, and resilient LCI H_2 infrastructure capable of moving LCI H_2 from geographically dispersed producers to a diverse spectrum of end users at demand centers. To balance the varying supply and demand requirements, LCI H_2 can either be produced where it is needed (on-site production) or transferred from large, centralized facilities (off-site production) to the demand centers, utilizing various infrastructure pathways of hydrogen transport, storage, and delivery.

Achieving a balanced portfolio of diverse LCI H_2 transportation, storage, and delivery alternatives to drive infrastructure development will require the integration of local infrastructure requirements with regional hubs, along with the national and international networks sustaining the hydrogen economy at-scale. There is no single infrastructure solution to satisfy every production facility, every distance or volume transported, and all various end-use requirements. As demonstrated by the regional case studies (see Chapter 4: Integrated Supply Chain), the choice of LCI H_2 transportation, storage, and delivery alternatives to meet region-specific supply and demand requirements will be driven by the volumes being transported, transport distance, technoeconomic factors, and end-use requirements, with federal, regional, state, and local net zero policies underpinning the adoption.

LCI H_2 transportation costs can dramatically raise the cost of delivered hydrogen based on region-specific attributes driving infrastructure pathways optimization, thus limiting the commercial viability of the burgeoning LCI H_2 economy (see Chapter 4: Integrated Supply Chain). One challenge that needs to be addressed is how to deliver safe, reliable, and affordable large-scale hydrogen from dispersed producers of LCI H_2 to various end-use sectors, while sustaining LCI H_2's economic viability. In terms of convenience and affordability, there is no one-size-fits-all transportation solution. A diverse portfolio of LCI H_2 transportation options (e.g., trucks, pipelines, rail, and ships) transporting hydrogen as gas, liquid, and hydrogen carriers (e.g., ammonia) will most likely coexist to help scale the LCI H_2 economy in the United States and globally.

For LCI H_2 to play a crucial role in powering a low-carbon economy, it must be stored in an efficient, safe, and cost-effective manner. Storage enables intermittent supply to be balanced (if produced using renewable energy feedstock), while also offering secure and reliable access to satisfy demand. Storage also allows for arbitrage—the process of procuring and storing a commodity when prices are low and selling it when prices increase—which helps reduce the overall cost of supplying energy. Multiple LCI H_2 storage pathways are essential for integrating supply and demand, meeting specific end-use requirements, and thus ensuring energy system resiliency and energy security. Long-duration LCI H_2 energy storage will scale over the long term via dispersed, low-cost geologic storage resources such as salt caverns. Given the geographic limitations of these geologic resources, more modular gaseous or liquid storage options will be essential to supporting volumetric and location-specific demand.

Last mile delivery to meet specific end-user demands is a critical component of the connecting infrastructure value chain and may involve the utilization of multiple hydrogen delivery pathways. For example, LCI H_2 transported over long distances using transmission pipelines to the city gate can be loaded onto trucks and delivered to a hydrogen refueling station or specific industrial end user via a low-pressure distribution pipeline infrastructure.

Carbon dioxide transportation and storage are important supporting infrastructure enablers for the United States to reach its decarbonization targets by 2050. The electric grid also plays a key role in the development of the LCI H_2 economy. Evaluating the role of LCI H_2 infrastructure with the electricity grid markets in the overall context of energy system reliability requires a better understanding of these markets to fully recognize the value of the infrastructure as part of future energy systems (see Section XI of this chapter).

As described in Section II of this chapter, developing LCI H_2 infrastructure across the Activation, Expansion, and At-Scale phases can have direct benefits that include enabling the use of LCI H_2 as a fuel or feedstock, supporting the growth of the LCI H_2 industry, ultimately reducing the cost of LCI H_2, and facilitating the integration of renewable energy sources. Hydrogen blending into existing natural gas infrastructure and repurposing of existing infrastructure to dedicated hydrogen service (once the fitness-for-service evaluations are complete) contributes to optimized infrastructure costs, minimization of environmental and community impacts, and ensuring that the existing energy infrastructure can be utilized as part of long-term operational viability (see Section VII of this chapter).

The development of LCI H_2 infrastructure can have a range of benefits that go beyond its direct impact on the hydrogen industry (as illustrated in Figure 3-4). Integrating the LCI H_2 infrastructure as part of the overall clean energy ecosystem in the United States can help advance GHG reduction goals, improve energy system resiliency, provide security of the energy supply, support job creation, and create clear market signals and long-term investment certainty for infrastructure development.

Understanding today's commercially mature, tried and tested hydrogen infrastructure will inform discussion of its larger-scale LCI H_2 infrastructure needs for tomorrow. Two mature and commercially viable connecting infrastructure systems currently operate in the United States in the Gulf Coast and Southern California (see Section IV.I of this chapter), including trucking, pipelines, gas, and liquefied storage in large-scale geologic salt caverns. Over several decades, the U.S. hydrogen industry has demonstrated the ability to produce, transport, store, deliver, and use hydrogen in a safe and reliable manner. This chapter addresses the key questions[6] associated with the expansion of LCI H_2 infrastructure to meet the future end-use demand, including:

- What integration and infrastructure requirements are needed to maximize hydrogen deployment for the identified market sectors and across the value chain?
- What hydrogen transportation carrier alternatives exist or could be developed and deployed (e.g., ammonia or other hydrogen carriers) in addition to the liquefaction, transportation, and use of elemental hydrogen?
- What research gaps exist and what is the path to address those gaps, including potential research roles for industry, academia, government, and national laboratories?

6 Appendix A: "Secretary of Energy Jennifer M. Granholm Letter to the National Petroleum Council." Department of Energy. November 8, 2021. https://www.npc.org/Hydrogen_Study-Request_Letter-2021-11-08.pdf.

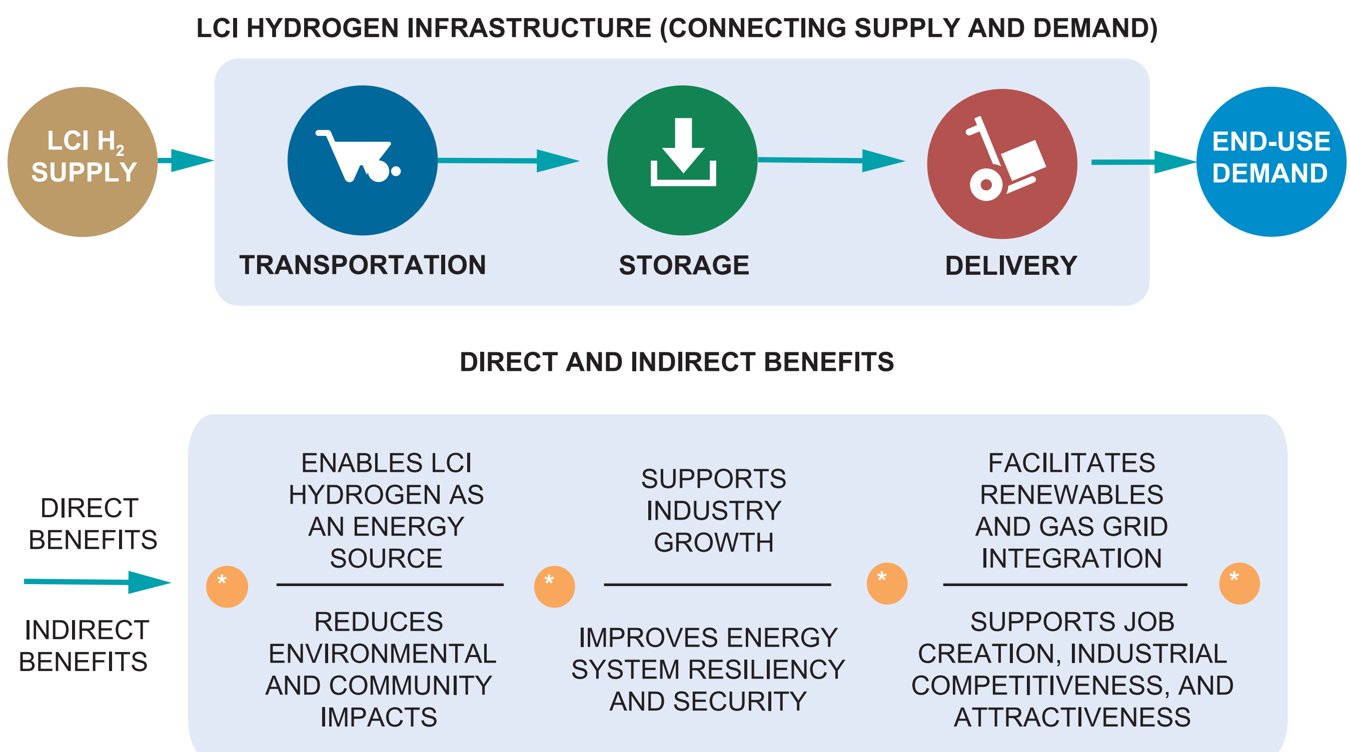


Figure 3-4. Integrating Hydrogen Infrastructure and Benefits

IV. LCI HYDROGEN TRANSPORTATION, STORAGE, AND DELIVERY PATHWAYS

A. Introduction

The choice of a particular technology alternative is driven mostly by technoeconomics and regional parameters, with federal, regional, state, and local emissions reduction policies underpinning the adoption. Multiple LCI H_2 transportation, storage, and delivery pathway alternatives will play a role in achieving a balanced portfolio of integrated infrastructure development to connect supply and demand.

This section of the chapter assesses the various pathways for transporting, storing, and delivering LCI H_2 to connect a diverse portfolio of current and future supply and demand requirements.

There is no single LCI H_2 infrastructure solution that can meet every production pathway, transport distance and volume, and end-use requirement (Figure 3-5). As a result, the selection of LCI H_2 infrastructure is primarily influenced by technoeconomics and regional parameters, with federal, regional, state, and local net zero policies underpinning the decision. The volume of hydrogen transported, the distance traveled, the end-user requirements, and regional characteristics (geographic, community, and environmental attributes) are key parameters that define and dictate the role and choice of transportation pathways. Multiple pathways for LCI H_2 infrastructure will be needed to integrate supply and demand.

Compared to other traditional energy sources, hydrogen is a gas with low volumetric density, but it offers a high energy density per unit of mass.[7] Due to its low volumetric density, hydrogen must be compressed (gas), condensed (liquefied), or transformed into other derivative carriers (ammonia and methanol) to be transported efficiently as the industry matures. Different kinds of transportation options are economically feasible depending on how hydrogen is compressed, condensed, or converted to other compounds. Trucks, pipelines, and ships are the potential methods of hydrogen transport today. Additional

7 DOE. 2023. "Hydrogen Storage." https://www.energy.gov/eere/fuelcells/hydrogen-storage.

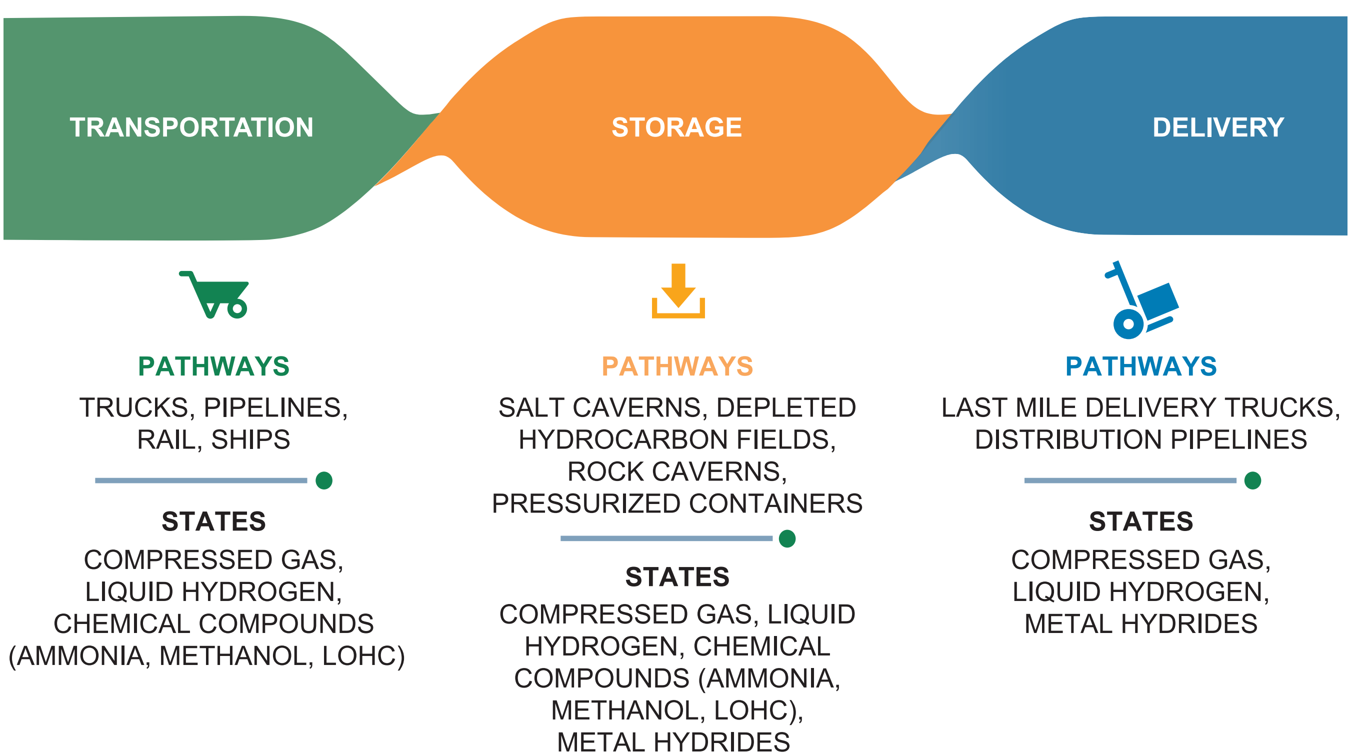


Figure 3-5. LCI Hydrogen Transportation, Storage, and Delivery Pathways

infrastructure systems that are often implemented at the point of receipt for end uses may include compression, storage, dispensers, meters, and impurity detection and purification systems.[8] Evaluation of hydrogen leakage rates across the various available transportation options is critical to ensure safety and mitigate potential climate impacts. (See Section X.C of this chapter.)

Multiple modes of LCI H_2 storage (pressurized containers, salt caverns, rock caverns, depleted oil/gas reservoirs, ammonia, metal hydrides, etc.) across the gas, liquid, or solid physical states may be required to integrate supply and demand of LCI H_2 and to suit end-use requirements. LCI H_2 as a longer-term, seasonal energy storage vector has the potential to improve the connecting infrastructure flexibility by balancing short-term supply unpredictability with seasonal demand swings, boosting energy supply security and resiliency. To fulfill this need, cost-effective, large-scale, and long-duration hydrogen storage technologies will be required.

To cover the complete spectrum of demands, an at-scale LCI H_2 economy will need to develop and deploy a combination of centralized, large seasonal storage and distributed, fast-cycling storage infrastructure (for stationary fuel cells or hydrogen refueling stations, etc.). There are several technological pathways for storing LCI H_2 and all of them employ pressurization, liquefaction, or chemical compounding to increase the density and lower the storage costs. Mature pathways, such as pressurized containers, liquefied storage facilities, salt caverns, and ammonia, are in commercial use today. Rock caverns, depleted hydrocarbon (oil and gas) fields, metal hydrides, and LOHCs are emerging storage pathways that are being intensively researched. The DOE's Subterranean Hydrogen Assessment, Storage, and Technology Acceleration (SHASTA) initiative intends to assess the feasibility of storing hydrogen or hydrogen/natural gas blends in subsurface environments. By using existing storage infrastructure (e.g., existing natural gas storage reservoirs) around the United States, the program could significantly accelerate and expand the deployment of hydrogen.[9] The GeoH_2 program at University of Texas at Austin is conducting subsurface hydrogen storage research and technology development, market feasibility analyses, and the exploration of novel subsurface hydrogen concepts.[10]

B. LCI Hydrogen Transportation and Distribution Pathways

1. Physical States of LCI Hydrogen Transportation and Delivery

Hydrogen in its natural state is a clear, odorless, nontoxic, and low-density gas. One of the major disadvantages of hydrogen is the low volumetric energy density compared to other fuels. The low volumetric density characteristics of hydrogen (see Chapter 1: Role of LCI Hydrogen) can be increased several ways to transport and deliver hydrogen efficiently based on the volumes and distances. The various states in which LCI H_2 can be transported include:

- **Compression:** Hydrogen generated at low pressures must be compressed before transportation.[11] The amount of compression required depends on a multitude of factors, including transportation and storage conditions, modes and distances, end-use application requirements, storage duration, supply chain efficiencies, etc.
- **Liquefaction:** The standard approach for increasing hydrogen density for bulk transport and storage has been hydrogen liquefaction and cryogenic liquid storage. Liquefying hydrogen by chilling it to -253°C (-423.4°F) significantly reduces its volume and increases its volumetric energy density. The liquefaction process is energy demanding, using around 30% to 36% of the energy contained in hydrogen.[12] Infrastructure requirements for liquefaction include

8 DOE. 2023. "Hydrogen Delivery." https://www.energy.gov/eere/fuelcells/hydrogen-delivery.

9 DOE. 2024. "Subsurface Hydrogen Assessment, Storage, and Technology Acceleration." https://edx.netl.doe.gov/sites/shasta/.

10 University of Texas at Austin, Jackson School of Geosciences. 2022. "About GeoH_2." https://geoh2.beg.utexas.edu/.

11 DOE. 2023. "Gaseous Hydrogen Compression." https://www.energy.gov/eere/fuelcells/gaseous-hydrogen-compression.

12 IRENA. 2022. "Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Technology Review of Hydrogen Carriers." https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II.

compressors needed to compress the hydrogen gas to the high pressures required for liquefaction, heat exchangers to cool the hydrogen gas as it is being compressed and purified, pumps to transfer the liquefied hydrogen as part of processing, and safety, control, and monitoring systems to ensure safe and efficient operation of the liquefaction facility. Regasification units will assist in converting liquefied hydrogen back to gaseous form before distribution.

- **Chemical compounds (synthesis/conversion):** Converting hydrogen into another molecule (ammonia, methanol, or LOHC) is another possibility for high-density hydrogen transport. Ammonia is already a chemical product that is traded on a global scale. It is feasible to convert hydrogen into ammonia and then back to hydrogen after transport. However some end users will need conversion facilities, which can be capital intensive. Still, ammonia has the benefit of liquefying at -33°C (-27.4°F), a higher temperature than pure hydrogen, resulting in reduced energy requirements. Direct use of ammonia as a fuel is also emerging in certain sectors, which would eliminate the efficiency loss of ammonia conversion to hydrogen.

  Methanol is a colorless, flammable liquid with a strong, pungent odor. It has a boiling point of 64.7°C (148.5°F). Methanol produced using renewable feedstocks (low carbon or renewable hydrogen) and biogenic carbon or carbon from direct air capture (DAC) has the potential to help decarbonize various industries (see Chapter 5: Demand). Methanol has a wide range of end users, including both industrial and consumer applications. It is used in chemical production as a feedstock, as a solvent, and as a fuel in marine[13, 14] and in internal combustion engines commonly blended with gasoline to create M85 fuel. It is also used in industrial processes to produce plastics, rubber, resins, and personal care products. Methanol as a hydrogen carrier can be transported using various methods from the point of production to meet the end-user demand, with liquid being the most common mode of transport.[15]

  According to the DOE, ammonia and methanol manufacturing account for the majority of global GHG emissions from chemicals, and both sectors rely on natural gas as a feedstock. If LCI H_2 is used, these processes can be decarbonized by more than 90%.[16]

  The LOHC pathway is an emerging technology in which hydrogen is bonded to a liquid hydrocarbon and then reconverted at the point of delivery. LOHC are hydrogen-reacting chemicals—Perhydro-dibenzyltoluene (PDBT) and Methylcyclohexane (MCH)—that may be reused several times as a hydrogen energy carrier. These oil-derived chemicals may be integrated into the existing liquid fuels infrastructure with minimal boil-off losses, because they stay in a liquid state at ambient temperatures, a useful feature for multimode transit routes.

Depending on the infrastructure and end-use applications, LCI H_2 can be transported in a variety of physical states. The best physical state for LCI H_2 transport will ultimately be determined by costs, risks, and end-user requirements.

2. Modes for LCI Hydrogen Transportation and Delivery

Currently, multiple modes of transportation and delivery of hydrogen are available, primarily determined by production facility locations in relation to existing demand centers, technoeconomics, and regional considerations, and supported by federal, regional, state, and local decarbonization policies.

Trucks: Trucks are widely used to carry hydrogen daily as they can transport it in any of the previously mentioned physical states. As a result, they are ideal for supplying hydrogen for dispersed consumers at shorter distances in local and urban areas. Today, compressed gaseous hydrogen

13 Methanex Corporation. n.d. "Methanol as a Marine Fuel." https://www.methanex.com/about-methanol/marine-fuel/.

14 Methanol Institute. n.d. "Marine Fuel." https://www.methanol.org/marine-fuel/.

15 Methanol Institute. n.d. "Fuel Cells." https://www.methanol.org/fuel-cells/#:~:text=Methanol%27s%20is%20a%20superior%20hydrogen.

16 DOE. 2023. "U.S. National Clean Hydrogen Strategy and Roadmap." https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap.

(CGH_2) and liquefied hydrogen (LH_2) are the most common forms of hydrogen transported by truck. Trucks are the most adaptable mode of hydrogen transport—ideal for short distances, as they can transport hydrogen in four different physical states, including CGH_2, LH_2, ammonia, and LOHC. CGH_2 is often transported in container trailers or tube trailers (in pressure-proofed seamless vessels). The containers are filled at the centralized hydrogen production facility and transported to the end user on trucks. Tube trailers with Type 1 pressure vessels are most widely used to transport hydrogen up to 250 kg at 200 bar, and Type III and Type IV pressure vessels can transport up to 1,000 kg of hydrogen at 500 bar.[17, 18] Type II pressure vessels have the highest pressure tolerance of up to 1,000 bar.[19] Some compressed hydrogen gas is delivered by road, utilizing transport pressure vessels known as Multiple Element Gas Containers (MEGC).[20] These systems are made up of modular bundles of gas cylinders. MEGC may be configured to match the size and characteristics of ISO standard containers, making them more suitable for intermodal transit.

Trucking using LH_2 is also widely established. Trucks often transport a trailer with a large tank of liquid hydrogen. LH_2 operates at a low temperature of -253°C (-423.4°F), which requires that tanks must be exceptionally well insulated. Liquefaction is more expensive than compression, making liquid hydrogen transport more expensive over shorter distances than CGH_2. Currently, hydrogen is delivered as a liquid across longer distances in super-insulated, cryogenic tanker trucks. Following liquefaction, liquid hydrogen is transferred to delivery trucks and transported to point of receipt, where it is reconverted to a high-pressure gaseous product for dispensing.[21] When transporting liquefied hydrogen using trucks, one of the main challenges is the boil-off of hydrogen.[22] Boil-off refers to the vaporization of liquid hydrogen due to heat exchange with the surroundings. Managing boil-off emissions (in lieu of venting)[23] to minimize environmental impact will be critical to ensure infrastructure safety and minimizing energy loss during transport. It requires vapor recovery systems to collect and oxidize, or recycle, the evaporated hydrogen.

Using trucks to transport hydrogen as LOHC is an emerging alternative option, because LOHCs are liquid in both their hydrogenated and dehydrogenated phases under normal conditions. Conventional diesel or gasoline trailers may be utilized for LOHC transportation. LOHC, however, involves high energy consumption requirements for dehydrogenation, leading to higher transportation costs.

Ammonia transportation is well established. Anhydrous (liquid) ammonia is carried via several modes of transportation. On land, ammonia is often carried as a pressurized liquefied gas by railway in tank cars, tanker trucks, and ammonia pipelines. A significant amount of ammonia is also carried on U.S. inland waterways using barges on the Mississippi River and its tributaries.

Methanol can be transported by truck in specially designed tanks or containers that are resistant to corrosion and equipped with safety features to prevent leaks or spills. Trucks are a flexible and convenient mode of transport and offer distribution flexibility, including last mile delivery from methanol terminals.

Pipelines (blended and dedicated): Pipelines are widely used to transport commodities (such as oil, chemicals, natural gas, hydrogen, etc.) in the United States and globally. Transporting gaseous hydrogen through pipes is an effective approach of

17 Reddi, K., Elgowainy, A., Rustagi, N., and Gupta, E. 2018. "Techno-Economic Analysis of Conventional and Advanced High-Pressure Tube Trailer Configurations for Compressed Hydrogen Gas Transportation and Refueling." *International Journal of Hydrogen Energy*. 43 (9): 4428–38. https://doi.org/10.1016/j.ijhydene.2018.01.049.

18 DOE. n.d. "Hydrogen Tube Trailers." https://www.energy.gov/eere/fuelcells/hydrogen-tube-trailers.

19 Yang, M., Hunger, R., Berrettoni, S., Sprecher, B., and Wang, B. 2023. "A Review of Hydrogen Storage and Transport Technologies." *Clean Energy*. 7 (1): 190–216. https://doi.org/10.1093/ce/zkad021.

20 Ortiz Cebolla, R., Dolci, F., and Weidner Ronnefeld, E. 2022. "Assessment of Hydrogen Delivery Options." Publications Office of the European Union. https://publications.jrc.ec.europa.eu/repository/handle/JRC130442.

21 DOE. n.d. "Liquid Hydrogen Delivery."

22 Ogden, Joan. 2004. "Hydrogen Delivery Model for H_2A Analysis: A Spreadsheet Model for Hydrogen Delivery Scenarios." https://escholarship.org/uc/item/5s85d149.

23 Boil-off can be potentially captured and recycled for liquefaction.

linking central or distributed production facilities to end users of hydrogen. Pipelines are best suited for transporting large volumes of hydrogen over long distances. As of 2022, there are 1,585 miles of gaseous hydrogen pipeline operated in the United States. Most of these pipelines (94%) are in the Gulf Coast region (Texas and Louisiana), linking significant hydrogen producers with well-established, long-term consumers (refineries, chemical processing facilities, ammonia, and methanol production).[24] Liquid-phase hydrogen carriers can also be transported using pipeline infrastructure. For instance, Nustar Energy's ammonia pipeline system spans approximately 2,000 miles and transports 1.5 MMTpa of anhydrous (liquid) ammonia in the United States.[25] Methanol can be transported by pipeline, although this is less common due to the corrosive nature of that chemical. If methanol is transported by pipeline, it is often mixed with gasoline or diesel for material compatibility. Methanol gasoline blends used as a transportation fuel are shipped to the product terminals through pipelines, barges, railcars, and trucks.[26, 27]

Rail and barge: Transportation of hydrogen by rail is possible but is not done today in the United States and globally. Future rail transport is expected to be limited because the costs (requiring multimodal transport and transfer infrastructure at offtake and receiving terminals) and safety risks are expected to exceed those of pipeline transportation.[28] Rail cars are used today to transport ammonia and methanol throughout the United States. Methanol can also be transported by barge, particularly when it is being shipped to locations that are not easily accessible by road or rail. Barge transport is more cost effective than truck or rail transport for long-distance shipments. Due to the affinity of methanol for residual water, the methanol handling systems must be kept dry to avoid water contamination.

Ships: There are three technically plausible options to transport hydrogen using ships: shipping LH_2 in cryogenic tankers, transporting hydrogen with carriers such as ammonia, and carrying LOHC in existing oil tankers. Each of these approaches involves three steps: converting or synthesizing gaseous hydrogen to LH_2 or to hydrogen carriers; transportation of LH_2 or its carrier in ships; and regasifying or reconverting the shipped molecules to gaseous hydrogen at the point of receipt or at end user under specified conditions (if molecular hydrogen is required and the hydrogen carrier cannot be used directly). Methanol is transported in a similar fashion, but it is not commonly considered a hydrogen carrier because it is utilized as fuel rather than as a separate source of hydrogen.

While transporting liquid hydrogen by truck is common, transporting it by ship is not. The Suiso Frontier is the only LH_2 ship currently in service, with an LH_2 storage capacity of approximately 33,000 gallons (1,250 m^3). In one voyage, around 75 MT of LH_2 can be transported.[29] After loading in Australia and traveling approximately 5,500 miles to Japan, the ship delivered its first LH_2 cargo in 2022 at the Port of Kobe (Japan). Suiso Frontier is a diesel-powered vessel that was conceived and produced as part of the CO_2-free Hydrogen Energy Supply chain Technology Research Association (HySTRA) project in 2019. The International Maritime Organization has awarded the HySTRA consortium (Iwatani, J-Power, Kawasaki Heavy, and Shell) preliminary authorization for an LH_2 shipping demonstration. It is also collaborating with other firms to make liquid hydrogen transportation more widely available by 2030.[30]

24 DOE. n.d. "Hydrogen Pipelines." https://www.energy.gov/eere/fuelcells/hydrogen-pipelines.

25 NuStar Energy. 2021. "Pipeline Transportation of Ammonia–Helping to Bridge the Gap to a Carbon Free Future."

26 Methanol Institute. 2016. "Methanol Use in Gasoline: Blending, Storage and Handling of Gasoline Containing Methanol." https://www.methanol.org/wp-content/uploads/2016/06/Blending-Handling-Bulletin-Final.pdf.

27 Methanol Institute. 2016. "Methanol Gasoline Blends: Alternative Fuel for Today's Automobiles and Cleaner Burning Octane for Today's Oil Refinery." https://www.methanol.org/wp-content/uploads/2016/06/Blenders-Product-Bulletin-Final.pdf.

28 Atlantic Council. 2021. "Hydrogen Policy Brief 3: Hydrogen Transportation and Storage."

29 Iakovenko, Valeriya. 2022. "Toward a New Era of Hydrogen Energy: Suiso Frontier Built by Japan's Kawasaki Heavy Industries." https://hydrogencouncil.com/en/toward-a-new-era-of-hydrogen-energy-suiso-frontier-built-by-japans-kawasaki-heavy-industries/.

30 IRENA. 2022. "Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Technology Review of Hydrogen Carriers." https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II.

Transporting ammonia or methanol using ships is mature and well established in the United States and globally, although larger ships may be optimal for transporting these molecules as energy carriers. Ammonia transport is an established technology with a mature worldwide supply chain that includes storage tanks and transport infrastructure. Ammonia, which is normally a gas, is historically delivered as a liquid over longer distances in cross-border commerce. Specialized ships, as well as regular liquefied petroleum gas (LPG) tankers,[31] in some cases may be employed to transport ammonia, increasing the scale of the infrastructure capable of transporting it. Ammonia is currently produced on a significant scale in the United States. Ammonia shipping (with terminals in more than 120 ports globally) is a mature hydrogen carrier pathway for longer intercontinental transportation routes. In addition to ammonia being utilized as a hydrogen carrier, it is also utilized directly as an industrial feedstock, as a marine fuel, in agriculture as fertilizer, and for power generation. Today, ammonia is commercially produced using the Haber-Bosch process, which involves synthesizing ammonia from hydrogen and nitrogen under high operating temperatures and pressures.

At the point of reception or end usage, ammonia can be reconverted (cracked) to retrieve hydrogen if not used directly as a fuel. Ammonia reconversion or cracking (also known as dissociation or splitting) is the process of converting ammonia into pure nitrogen and hydrogen. Ammonia cracking needs high temperatures—e.g., 950°C–1,050°C (1,742°F–1,922°F) without the use of a catalyst—or lower temperatures of 900°C (1,652°F) with the use of a catalyst to expedite the reconversion process. Conventional catalysts are based on nickel and require temperatures ranging from 600°C to 900°C (1,112°F–1,652°F), whereas alternative catalysts utilize rare minerals like ruthenium or iridium and require temperatures ranging from 350°C to 600°C (662°F–1,112°F). The next generation of catalyst (potentially lithium or sodium) may support even lower process temperatures of 250°C (482°F). A minimum of 5% to 6% of the energy contained in ammonia can be used by an ammonia cracker. Furthermore, thermal energy losses in the cracker are between 4% to 7%.[32]

Methanol is shipped in specially designed vessels that are equipped with tanks for carrying liquids. Methanol tanker ships are equipped with pumps, piping, and other equipment to load and unload methanol at ports and terminals and are available in various capacities. In addition to the tanker ships, the shipping infrastructure for methanol includes ports and terminals where methanol is loaded and unloaded (and sometimes extends to the facilities where the methanol is cracked to release hydrogen). These facilities include loading arms, transfer pumps, and other equipment to safely transfer methanol from the tanker ship to storage tanks, other transfer vessels, and processing facilities to meet the end-use needs. LOHCs (with their chemical similarities to oil products) may be transported in conventional oil product containers or tankers, an adaptability that should make them a popular mode of hydrogen transportation. While LOHCs are technically well known, they have not been substantially used on a commercial scale. Limited commercialization to date will show LOHC shipping beginning with small-scale trials using standardized containers aboard container ships.

Hydrogenious LOHC Technologies and Chiyoda Corporation (Chiyoda) are two of the current players in LOHC hydrogen transportation carrier pathway. Hydrogenious, which now provides small-scale containerized LOHC units, employs benzyltoluene as a carrier with the goal of developing larger units with capacities between 1 and 5 metric tons per day (MTpd). Chiyoda has pioneered the methylcyclohexane-based SPERA Hydrogen® technology for storing and transporting hydrogen utilizing the LOHC technology. Chiyoda began with LOHC catalyst development in 2008, followed by a demonstration plant in 2014, and worldwide shipping demonstration in 2020. Chiyoda collaborated with

31 Bureau Veritas. "An Overview of Ammonia as Fuel for Ships." n.d. https://marine-offshore.bureauveritas.com/shipping-decarbonization/future-fuels/ammonia#:~:text=Ammonia%20is%20a%20widely%20traded.

32 IRENA. 2022. "Global Hydrogen Trade to Meet the 1.5°c Climate Goal: Technology Review of Hydrogen Carriers." https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II.

Mitsubishi Corporation, Mitsui, and Nippon Yusen Kabushiki Kaisha as part of the Advanced Hydrogen Energy Chain Association for Technology Development initiative to transport hydrogen for use in power generation from Brunei to Japan (approximately 3,100 miles) utilizing its proprietary LOHC technology.[33]

According to the International Renewable Energy Agency, by 2030, the most attractive long-distance transportation carriers (for 6,200 miles) will be ammonia and LOHC, with a transportation cost ranging from $2.5 to $4.5/kg H_2.[34] The lower bound cost depicts the most optimistic scenario, in which innovation has led to technological advancement and several pilot programs have gained technology commercialization. Transporting liquefied hydrogen over long distances may be expensive since it requires development and deployment at a larger scale and may not be cost competitive by 2030.

C. Key Parameters That Define/Dictate the Role of Transport and Delivery Pathways

The choice of a specific transportation and delivery option/pathway is defined by the volume of hydrogen being transported, the transport distance, and end-use requirements. Regional characteristics (geographic, community, and local environmental considerations such as the availability of water) also influence the choice of transportation and delivery pathways.[35]

The cost economics of hydrogen transportation is heavily dependent on the volume being transported and the transport distance as shown in Figure 3-6. Transporting compressed gaseous hydrogen via trucks might be optimal for smaller volumes and shorter distances (local, urban, and intercity), but to transport similar volumes on trucks at greater distances (intercity or interstate), liquid hydrogen is most suitable. Transportation and delivery pipelines are a cost-effective means for hydrogen transportation and delivery as hydrogen volumes grow and transport distances increase to meet local, urban, and intercity demands. Ships are the most appealing option to transport the highest volumes of hydrogen for very long distances and for export/import as part of cross-border intercontinental trade. The transport of hydrogen through energy carriers is favored for situations where long distances and large volumes are required.

D. Status of Current Transportation and Delivery Pathways

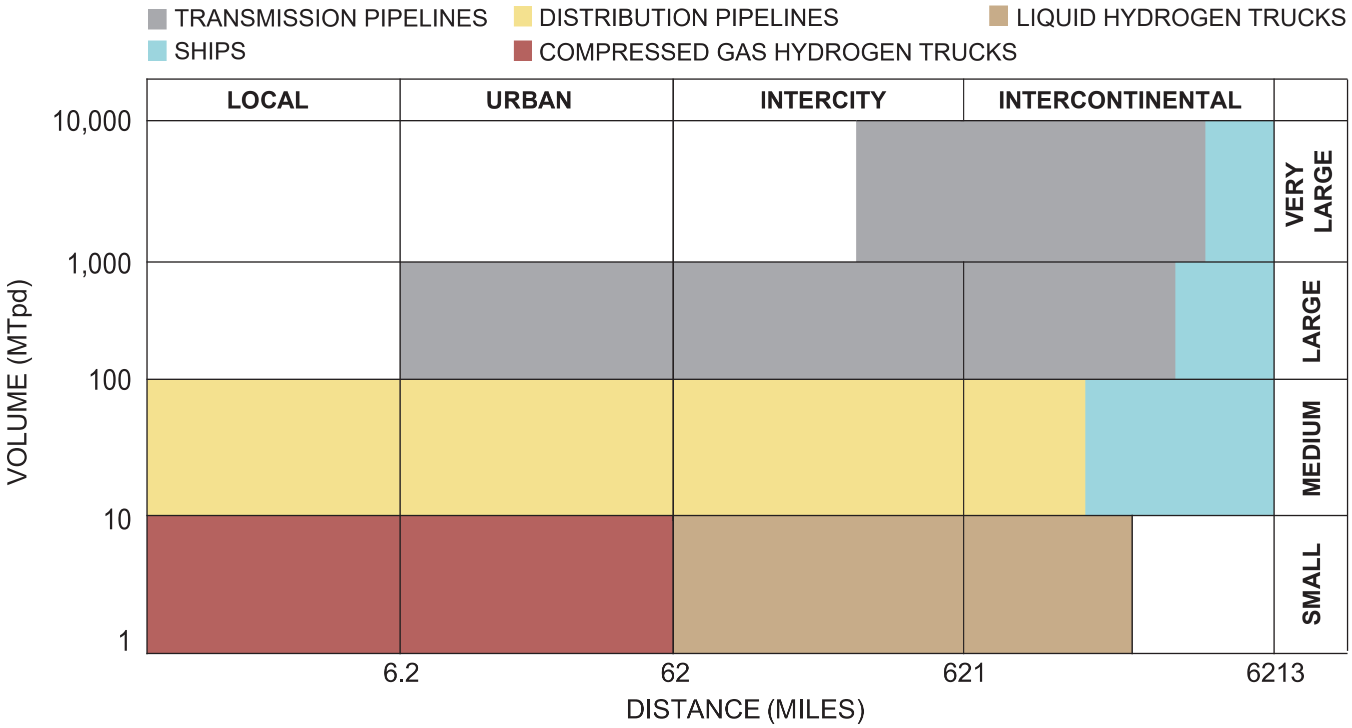
Many of the transportation and delivery pathways such as CGH_2, LH_2, and ammonia are mature and commercialized in the United States and globally, leveraging either trucks, pipelines, or ships depending on the state of hydrogen being transported. Trucks have already demonstrated versatility to carry hydrogen and offer a commercially feasible solution to transport and deliver it (as CGH_2, LH_2, and ammonia) over shorter distances. Pipelines have demonstrated their role as a transport carrier for CGH_2 and ammonia over longer distances domestically. Ships are widely used to transport ammonia over very long distances as part of international trade flows. The viability of emerging technologies is being demonstrated at various locations. For instance, as a part of the H_2Sektor pilot project, the Hydrogenious LOHC technology was deployed at the hydrogen filling station in Erlangen, Germany. Tanker trucks with a total gross capacity of 45,000 liters were used to transport LOHC to the hydrogen filling station.[36] These demonstration projects are pushing the envelope on emerging hydrogen carrier technologies. Section IV.I of this chapter further evaluates the current landscape of hydrogen transportation, storage, and delivery infrastructure specifically deployed in the United States.

33 IRENA. 2022. "Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Technology Review of Hydrogen Carriers." https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II.

34 IRENA. 2022. "Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Technology Review of Hydrogen Carriers." https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II.

35 DOE. 2013. "Hydrogen Delivery Technical Team Roadmap." https://www.energy.gov/eere/fuelcells/articles/hydrogen-delivery-roadmap.

36 FuelCellWorks. 2022. "Worldwide Novelty: Hydrogenious Supplies Hydrogen Filling Station in Erlangen/Germany via Liquid Organic Hydrogen Carriers." https://fuelcellsworks.com/news/worldwide-novelty-hydrogenious-supplies-hydrogen-filling-station-in-erlangen-germany-via-liquid-organic-hydrogen-carriers/.



Source: Modified from IRENA, 2022, "Global Hydrogen Trade to Meet the 1.5C Climate Goal, Technology Review of Hydrogen Carriers."

Figure 3-6. *Transportation Pathway Alternatives Based on Volume and Distance*

E. LCI Hydrogen Storage Pathways

As discussed previously, the LCI H_2 economy will require plentiful and reliable storage. Multiple technologies and pathways exist to meet variable demand needs, from small-scale, distributed LCI H_2 storage for daily demand to seasonal storage to satisfy demands from several days to weeks. Both small and large volumes of LCI H_2 storage resources will be needed for a resilient future LCI H_2 economy to ensure supply can always meet demand.

A broad portfolio of LCI H_2 storage infrastructure pathways will be necessary to meet various local and regional market demands in the United States by 2050. The LCI H_2 storage infrastructure at-scale will rely on both geologic subsurface facilities (salt caverns) storage and aboveground storage methods. Other geologic, subsurface storage options, such as depleted oil and gas reservoirs, will be used when subsurface storage is unavailable in certain regions due to unequal distribution of geologic storage potential (salt caverns) across the United States. The repurposing potential of existing natural gas or liquid hydrocarbon storage systems is plausible but will need additional research and investments.

Several archetypical case studies conducted in the EU show that deploying repurposed storage infrastructure reduces the operational and investment costs of the energy system. The case studies also indicate that the access to large-scale hydrogen storage infrastructure lowers the overall system costs.[37] An integrated network of LCI H_2 storage infrastructure technologies supporting both above- and belowground geologic storage resources in the United States will facilitate cost reduction and improve reliability. With the expansion of the LCI H_2 economy, regions with limited access to storage will benefit from the integrated network (see Section V of this chapter).

LCI H_2 storage infrastructure plays an important role to connect supply and demand and to balance energy needs, especially when LCI H_2 is produced from intermittent renewable resources

37 Gérard, Frank. 2022. "The Role of Renewable Hydrogen Import and Storage to Scale up the EU Deployment of Renewable Hydrogen." https://commission.europa.eu/system/files/2022-01/entec_h2_study_workshop_31st_jan_2022_v2.pdf.

(like solar and wind). To meet future demand, hydrogen storage technologies will most likely be deployed in stages. Salt caverns and pressurized hydrogen storage vessels are the most likely dominant, currently mature, and commercially viable technologies in the short term. Other emerging storage pathways (rock caverns, depleted oil and gas reservoirs, ammonia, LOHC, and metal hydrides) may offer potential at-scale solutions for LCI H_2 storage in the future.

1. Modes of LCI Hydrogen Storage

The following section details the multiple modes of LCI H_2 energy storage to support the multiple states of hydrogen as discussed in Section IV.B.1 of this chapter.

a. Gaseous Storage

Salt caverns: Salt caverns currently offer the most cost-effective way to store large volumes of hydrogen for periods of several weeks or longer compared to other storage pathways. Salt caverns offer a cost-effective way to store hydrogen at-scale (size and storage capacity), but availability is constrained by geography and geological distribution of salt deposits.

Salt caverns are typically developed by solution mining large cavities into salt domes by drilling a well and injecting water. The high-salinity environment of the domes reduces the likelihood of hydrogen bioconversion and/or loss due to the absence of subsurface microorganisms and as a result, salt caverns are considered generally a leak-tight storage system and environmentally inert. Hydrogen storage in salt caverns is a proven technology, with three facilities in the United States (Clemens Dome, Moss Bluff, and Spindle Top; see Section IV.H of this chapter) that are currently operational. A new salt cavern will be commissioned in 2025 as part of the Intermountain Power Project (IPP) in Utah.[38] IPP's proximity to a major geologic salt cavern formation in the western United States makes it an attractive location for storing large volumes of hydrogen supporting future regional hydrogen hubs. The IPP project also offers access to existing electric transmission lines near the interstate natural gas transmission pipelines. The Advanced Clean Energy Storage project in Delta, Utah, intends to employ electrolysis to convert renewable energy into hydrogen, then store the energy in solution-mined salt caverns for seasonal, dispatchable storage. The first project, which would convert and store up to 100 MTpd H_2, is now under development and will begin commercial operations in mid-2025 to support the IPP Renewed initiative.[39]

Since the salt caverns' infrastructure development potential is geographically constrained in the United States (confined only to a few specific geographic regions), rock caverns and depleted oil and gas reservoirs (hydrocarbon fields) offer the next best large-scale solutions for geologic LCI H_2 storage. Additional research is required to prove that these emerging technologies are technically viable in the future.

Depleted hydrocarbon fields: Depleted hydrocarbon reservoirs account for the majority of existing underground gas storage sites that are potentially available for storing LCI H_2 in the United States. The existing reservoirs offer large storage volumes and well-understood geological characteristics. The inherent reservoir engineering and facilities limitations of storing hydrogen in depleted hydrocarbon reservoirs include the risk of stored hydrogen reacting with residual hydrocarbons, the potential for reduced hydrogen purity, and potentially requiring purification to meet specifications after withdrawal, which can be expensive. In addition, based on reservoir temperature and salinity conditions that are conducive to microorganism growth, the microorganisms in the storage subsurface can react with hydrogen to form methane, hydrogen sulfide, etc. Besides losing hydrogen to microbial and geochemistry, one other significant concern is the risk of hydrogen leakage through small fractures/cracks because of its low molecular weight and high compressibility. To overcome these complex challenges, hydrogen storage in depleted reservoirs will require a comprehensive site selection, characterization, and

38 Intermountain Power Agency. n.d. "IPP Renewed." https://www.ipautah.com/ipp-renewed/.

39 Chevron. 2023. "Chevron Acquires Majority Stake in the Advanced Clean Energy Storage Hydrogen Project in Delta, Utah." https://www.chevron.com/newsroom/2023/q3/chevron-acquires-majority-stake-in-advanced-clean-energy-storage-project-delta-utah.

evaluation process. This option has a low technology readiness level because of the lack of industry experience.

There are only two projects in operation globally (the HyChico Project in Argentina[40] and the Underground Sun Conversion Project in Austria[41]) offering 2.5 GWh of hydrogen storage with a plan to store hydrogen in a depleted gas field.[42] Further research, development, and demonstration of hydrogen storage pilot projects would be needed in the United States to advance the current low technological and commercial readiness levels for this emerging storage pathway.

Rock caverns: Potentially large volumes of gaseous hydrogen storage can be offered in underground rock caverns that are lined with steel or plastic to reduce the likelihood of hydrogen leakage or losses from reactions with the rock surface. Unlined rock caverns also offer the potential to store hydrogen, but further analysis specific to each cavern is needed to ensure the role of microbial reactions that could impact hydrogen purity of storage.

Globally, rock caverns are yet to be tested in hydrogen storage service and therefore are lower on the technical and operational readiness rating for wide-scale implementation. Since rock caverns need to be mined to create storage space, development tends to be pricier than salt cavern storage. The higher costs of storage in rock caverns can be a potential constraint for development unless abandoned tunnels or mines can be leveraged. Rock caverns are currently being used to store natural gas and liquid fuels (crude oil and LPG). Lined rock caverns seem to have minimal storage losses and are expected to offer high hydrogen purity after withdrawal from storage. Lined rock caverns offer alternatives to store both blended hydrogen and natural gas mixtures or pure hydrogen.

Pressurized containers: Pressurized containers offer both stationary and mobile storage and are already in use for transport and low-volume gaseous hydrogen storage (ranging from a few kilograms to store and supply hydrogen fuel cell vehicles to several hundred kilograms to dispense hydrogen at a refueling station). Pressurized hydrogen storage containers offer flexibility and ease of mobility. Four types of pressurized hydrogen storage containers are available (based on the type of material construction and pressure rating): Type I, II, III, and IV. Type I containers are constructed using steel or aluminum. Type II containers are metallic and partly coated in fiber composite to support the structural load. Type III containers incorporate a metal liner with a full composite wrap, and Type IV containers are made fully of composite materials. Pressurized containers can be stacked and loaded on trailers or aggregated together in clustered storage systems, thereby offering flexibility as a preferred solution for last mile delivery of hydrogen and for distributed on-site storage. Hydrogen containers can be cycled frequently based on the specific end-user needs. Large-scale or long-term storage of hydrogen in containers is expensive compared to underground geologic storage (e.g., salt caverns). See Section V.B.5 of this chapter.

Linepack: Pipeline infrastructure can also provide implicit storage options through linepack. Linepack refers to the compressed gas that remains in a pipeline during periods of low or no flow and could play an important role in pipeline hydrogen storage. Linepack can assist with peak shaving demand, which entails using stored hydrogen during peak demand periods to alleviate strain on the production and delivery networks. Linepack storage could be very effective in balancing the unpredictable, intermittent nature of renewable energy sources for LCI H_2, as well as giving operational flexibility to manage variations in demand and supply without requiring rapid adjustments in production or transit flow.

b. Liquid Storage

LCI H_2 can be stored either as liquefied hydrogen or as liquid carrier compounds:

Liquid hydrogen: Large amounts of hydrogen can be stored in a liquid state in stable condition

40 Hychico. 2018. "Underground Hydrogen Storage" https://hychico.com.ar/eng/underground-hydrogen-storage.php.

41 Austria AG Renewables and Gas. 2021. "Underground Sun Conversion-Flexible Storage." https://www.underground-sun-conversion.at/en/.

42 International Energy Agency. 2023. "Global Hydrogen Review 2023." https://iea.blob.core.windows.net/assets/8d434960-a85c-4c02-ad96-77794aaa175d/GlobalHydrogenReview2023.pdf.

at -253°C (-487.4°F), enabling efficient transport of hydrogen over longer distances like liquefied natural gas (LNG), catering to specific regions or demand centers where no other hydrogen transport and storage infrastructure exists. A key barrier for this storage pathway is the extremely low temperatures required to achieve liquefaction, necessitating the need for additional infrastructure to handle cryogenic conditions and reduce the thermal losses and potential boil-off during storage impacting overall efficiency. Liquefaction of hydrogen also demands high energy consumption to attain and maintain cryogenic conditions for storage.

LH_2 is stored in spherical tanks designed to help reduce the surface area and heat transfer losses and maintain cryogenic conditions for storage. The largest spherical LH_2 storage infrastructure in the United States is a NASA facility capable of storing 4,900 m^3 of LH_2 to support NASA's Artemis missions to the moon and Mars.[43] In 2020, Kawasaki Heavy Industries commissioned the largest LH_2 storage facility[44] globally capable of storing 10,000 m^3 and enhancing the technical and commercial scaling of storing LH_2.

Liquid ammonia: Storing hydrogen as liquid ammonia is a mature technology and is proven in large storage tanks and transport vessels. In its liquid state, ammonia offers higher hydrogen density when compared to liquid hydrogen. This makes storing hydrogen as liquid ammonia commercially appealing, since storing the same amount of hydrogen as liquid ammonia requires significantly less volume than storing liquid hydrogen or compressed hydrogen gas. Liquid ammonia allows for large-scale storage (at atmospheric pressure) with capacities of up to 50,000 MT. LPG storage tanks (which have a similar design and duty to ammonia tanks) have already been constructed with up to 130,000 m^3 capacity (about 89,000 MT).[45] Liquid ammonia storage is not geographically constrained and offers the ability to scale easily using a modular storage infrastructure design.

Liquid methanol: Methanol is stored as a liquid in specially designed tanks or containers that are resistant to corrosion and are equipped with safety features to prevent leaks or spills. These tanks and containers may be made from stainless steel, fiberglass, or polyethylene, which can withstand methanol's corrosive nature.

Methanol storage tanks and containers are frequently located at the production facility or at a terminal near the point of use. In some cases, methanol may be stored in underground storage tanks, although this is less common due to the corrosive nature of methanol and the potential for leaks or spills.

LOHC: LOHC as a hydrogen storage pathway is well understood from a technology perspective but is still not fully commercialized. As discussed in Section IV.B.1 of this chapter, companies developing LOHCs[46] are developing commercialization pathways for them. LOHC storage offers higher-density characteristics when compared to pressurized containers but offers lower density of storage when compared to LH_2 and ammonia.

c. Solid-State Storage

Metal hydrides: Storage of hydrogen using metal hydride compounds is technically feasible but needs further research and commercial-scale demonstration and deployment to be widely accepted, especially for storing large quantities of hydrogen. The stored hydrogen from metal hydrides is regenerated by dehydriding the host compound by heating or depressurizing. After desorption, the metal hydride can be rehydrided to store hydrogen again as part of the recycling process. Metal hydride storage utilizes powdered metals and can result in a very heavy storage infrastructure (by weight) depending on the type of metal considered for storage. Multiple metals can be utilized as a storage medium, including magnesium, nickel, palladium, lithium, aluminum, titanium, lanthanum, etc. Tanks operating at low pressures are often used to host metal hydrides

43 NASA. 2021. "Kennedy Plays Critical Role in Large-Scale Liquid Hydrogen Tank Development." https://www.nasa.gov/centers-and-facilities/kennedy/kennedy-plays-critical-role-in-large-scale-liquid-hydrogen-tank-development/.

44 Kawasaki. 2020. "Kawasaki Completes Basic Design for World's Largest Class (11,200-cubic-meter) Spherical Liquefied Hydrogen Storage Tank." https://global.kawasaki.com/en/corp/newsroom/news/detail/?f=20201224_8018.

45 Ecuity, Engie, STFC, and Siemens. 2020. "Ammonia to Green Hydrogen Project: Feasibility Study." https://assets.publishing.service.gov.uk/media/5ea1705fd3bf7f7b4cadb7c5/HS420_-_Ecuity_-_Ammonia_to_Green_Hydrogen.pdf.

46 Such as Chiyoda Corporation, Hydrogenious Technologies, etc.

for hydrogen storage. The low-pressure operating characteristics make that storage option safer compared to other storage pathways like pressurized hydrogen storage.

Metal hydride storage has potential drawbacks, including degradation of storage capacity after multiple cycles of the hydride medium since the metal hydride compounds tend to lose their ability to store hydrogen over time. Metal hydride storage infrastructure also needs large amounts of cooling and heating as part of hydrogen absorption and desorption.

d. *Emerging Storage Technology Pathways*

The metal-organic frameworks (MOFs) have the potential to provide cost-competitive hydrogen storage options. The sponge-like MOFs have a high surface area for the hydrogen molecule to adsorb to the surface of the cavities. They also have a simple charge and discharge mechanism, which is favorable for end-use applications like backup power. MOFs do not require high temperatures to discharge the hydrogen, making it less energy intensive. When compared to compressed hydrogen storage, MOFs have a higher system-level energy density. Some of the drawbacks of MOFs include high fabrication costs, poor selectivity, and low capacity toward hydrogen, and difficulties in recycling and regeneration of MOFs. For these reasons, further RD&D is required to commercialize the technology.[47, 48]

Cryo-compression of hydrogen is used to overcome the disadvantages of compressed gaseous hydrogen and liquid hydrogen at atmospheric pressure. The hydrogen at cryogenic temperatures (not as low as liquefaction temperatures at atmospheric pressure) is stored in a pressurized container. Cryo-compressed hydrogen storage has several advantages when compared to gaseous compressed hydrogen and liquid hydrogen at atmospheric pressure (an overall higher energy density, volumetric efficiency, gravimetric capacities, and reduced boil-off effects). This results in reduced in-vessel overpressurization and longer thermal endurance. The cryo-compressed storage systems should have the endurance for low temperatures and high pressures. These factors make the systems complex and hard to implement on a commercial scale. Stringent management and monitoring of the thermal insulation levels in these systems is required for safe operations. This results in higher maintenance costs and energy needs for operation when compared to compressed hydrogen gas and liquid hydrogen at atmospheric pressure. To overcome these technical challenges, further RD&D is required to develop cryo-compression for commercial applications.[49]

F. Key Parameters Defining the Role of Hydrogen Storage

The choice of a storage pathway is dependent on multiple criteria, including 1) required working capacity of the storage technology to meet swings in supply and demand; 2) distances between supply and demand centers; 3) differences in hydrogen spot prices and seasonal price differentials; 4) the current and future states of cost economic viability of storing hydrogen using a particular technology, the expected storage cycling frequency, potential storage losses, levelized cost of storage (current and future); and 5) key technical parameters, including pressure rating, storage density, expected purity of hydrogen after release from storage, parasitic load consumed to store hydrogen, geographic availability of storage resources, community, safety, and environmental impacts of storage, and technology and commercial readiness of storage technologies.

A comprehensive analysis is needed to ascertain the key characteristics for each storage technology for a comparison, including all the previously identified key parameters. This effort will allow scoring and prioritization of each storage pathway potential for future infrastructure development.

47 Julin, Kiran. 2022. "Emerging Hydrogen Storage Technology Could Increase Energy Resilience." https://newscenter.lbl.gov/2022/05/11/emerging-hydrogen-storage-technology-could-increase-energy-resilience/.

48 Vikrant, K., Kumar, V., Kim, H-K., and Kukkar, D. 2017. "Metal–Organic Frameworks (MOFs): Potential and Challenges for Capture and Abatement of Ammonia." *Journal of Materials Chemistry* A 5 (44): 22877–96. https://doi.org/10.1039/C7TA07847A.

49 Argonne National Laboratory. 2009. "Technical Assessment of Cryo-Compressed Hydrogen Storage Tank Systems for Automotive Applications Nuclear Engineering Division." https://www.energy.gov/eere/fuelcells/articles/technical-assessment-cryo-compressed-hydrogen-storage-tank-systems.

This type of proposed analysis is beyond the scope of this study.

As the LCI H_2 economy evolves from Activation to At-Scale maturity supporting multiple end-use sectors, assessing the need for SHR in the United States during the Expansion or At-Scale phase could help ensure the reliability of LCI H_2 supply to critical end-use sectors and promote overall resilience in the face of potential disruptions (driven by geopolitical, cybersecurity, terrorism, etc.). The presence of SHR can boost market confidence and attract investments in the hydrogen sector. These reserves can help reduce supply uncertainty and encourage private sector participation in the development of hydrogen-related technologies and infrastructure. The SHR established in a mature market can aid in international cooperation and collaboration. Shared reserves or agreements on emergency response mechanisms could strengthen diplomatic ties and contribute to a more stable global energy landscape for LCI H_2.

G. Hydrogen Refueling Infrastructure

1. Introduction

The choice and development of hydrogen transportation, storage, and delivery infrastructure can be influenced by the unique end-use characteristics and corresponding demand volumes. This can be illustrated through the development of hydrogen refueling stations (HRS) and the associated infrastructure discussed in this section.

HRS act as a critical enabler of hydrogen fuel cell vehicle adoption in the mobility sector and driver of hydrogen demand. The availability of a comprehensive refueling infrastructure network in the United States will help instill supply and demand certainty for various end-user mobility needs and thus foster greater adoption of fuel cell vehicles. This confidence encourages more people to consider fuel cell vehicles as a practical and accessible option. As discussed in Chapter 5: Demand, the vehicle transportation sector is exploring a range of solutions to reduce emissions and attain a sustainable net zero carbon ecosystem, including conventional technologies such as internal combustion engines powered by renewable natural gas, biofuels, hydrogen, and other eFuels. LCI H_2, along with other clean fuels and battery electric powertrains, plays an important role in the mobility market, including light-, medium-, and heavy-duty truck markets, as well as transit buses, aviation, rail, and marine applications.

As evident in California, driven primarily by the state policies,[50] a growing public and private Hydrogen Refueling Infrastructure (HRI) network is helping to support various mobility end-user demand for hydrogen. This includes forklifts, passenger cars, transit buses, and heavy-duty trucks. California's HRI network currently operates 59 light-duty HRS supporting approximately 16,700 fuel cell cars and 66 fuel cell buses.[51] The HRS in California are designed to meet the SAE International J2601 fueling standards to ensure the safe dispensing of hydrogen into fuel cell light-duty vehicles. According to the DOE, some of those stations could also safely fuel heavy-duty vehicles.[52] Infrastructure-based incentives, such as California's Low Carbon Fuel Standards-Hydrogen Refueling Infrastructure Credit Program (LCFS-HRI),[53] have enabled the infrastructure development by providing credits to participating station operators based on the difference between station capacity and fuel sales, allowing credit generation based on capacity for a period of 15 years. Lessons learned from California can help set an accelerated development path toward a safe, reliable, and resilient HRI framework across the United States.

a. Hydrogen Refueling Station Elements

A typical HRS consists of several system components that work together to produce, process, store, and dispense hydrogen. These system

50 Assembly Bill (AB) 8 (2013) provides $20 million in annual funding to support the construction of 100 hydrogen-fueling stations. Executive Order (EO) B-48-18 doubles California's construction goal for hydrogen refueling stations, by establishing new targets of 200 stations and 5 million zero emissions vehicles by 2030.

51 Hydrogen Fuel Cell Partnership. 2024. "By the Numbers: FCEV Sales, FCEB, & Hydrogen Station Data."

52 Koleva, Mariya and Marc Malaina. 2020. "Hydrogen Fueling Stations Cost Originator." https://www.hydrogen.energy.gov/pdfs/21002-hydrogen-fueling-station-cost.pdf.

53 California Air Resources Board. 2021. "LCFS ZEV Infrastructure Crediting." https://ww2.arb.ca.gov/resources/documents/lcfs-zev-infrastructure-crediting.

components work in an integrated fashion to ensure safe, reliable, and efficient operation of the station. A few key components are described in the following paragraphs.

HRS hydrogen supply: Many hydrogen-supply pathways can support an HRS. This includes delivery of hydrogen to the station via tube trailers, distribution pipelines, or on-site production. The choice of hydrogen-supply method to the refueling station depends on various factors such as production and delivery costs, capacity of the station, feedstock availability, geographic location, land availability, access to supporting utility infrastructure, and environmental and socioeconomic considerations.

HRS compression and cooling systems: Hydrogen is often compressed to increase its density, allowing for more fuel to be stored in the same amount of space.

HRS on-site hydrogen storage: The hydrogen feedstock needs to be stored safely until it is dispensed into vehicles. HRI uses high-pressure storage tanks or cryogenic storage systems to keep hydrogen in a gaseous or liquid state, respectively. High-pressure storage systems use compressed gas cylinders, while cryogenic systems store hydrogen at extremely low temperatures.

HRS dispensing system: The hydrogen dispensing system is responsible for transferring hydrogen from the storage system to the vehicle's hydrogen storage tank at the proper temperature (cooling is required to avoid overheating the vehicle fuel tank). The dispensing system includes hoses, nozzles, and safety features to ensure a secure connection and to prevent any leaks during the fueling process.

HRS equipment support and safety systems: Additional support systems include safety-related equipment leakage monitoring, pressure sensors, control and monitoring systems, flame and gas detection systems, ventilation, and safety protocols to minimize risks associated with hydrogen handling.

Based on the station (compressed gas or liquid hydrogen), the type of equipment used to transfer the delivered hydrogen to the station, and refueling station storage and handling configurations, there are currently four potential pathways for Fuel Cell Electric Vehicle (FCEV) refueling at an HRS as shown in Table 3-1.

2. Role of Hydrogen Refueling Infrastructure to Support Demand

One of the critical factors driving the widespread adoption of hydrogen fuel cell vehicles across the various mobility end-user applications is the establishment of a robust and accessible HRI. This infrastructure serves as the backbone of the hydrogen mobility ecosystem, facilitating the refueling needs of light passenger vehicles, medium-duty trucks, and heavy commercial vehicles alike. The development of a safe, reliable, resilient, and fast fueling HRS network is a key market enabler for the faster transition to hydrogen fuel cell vehicle adoption and to support sector decarbonization.

Developing an HRS network stimulates investments across the entire infrastructure value

Station Delivery	Transfer Mechanism	Handling Prestorage	Station Storage	Handling Poststorage	FCEV Onboard Storage
CGH_2	Gas Compressor		CGH_2 (~500-1000 bar)	Storage Switching Bank	CGH_2 (350-700 bar)
LH_2	Pump	LP Vaporization, Gas Compressor	CGH_2 (~500-1000 bar)	Storage Switching Bank	CGH_2 (350-700 bar)
LH_2	Pump	Cryo Compressor	CGH_2 (350-700 bar)	HP Vaporization	CGH_2 (350-700 bar)
LH_2	Pump		LH_2 (LP)	Cryo Compressor (15+ Bar)	sLH_2 (-15 bar max)

Notes: CGH_2 = compressed gas; LH_2 = liquid hydrogen; LP = low pressure; HP = high pressure; sLH_2 = subcooled LH_2.

Table 3-1. *Pathways for FCEV Refueling at Hydrogen Refueling Stations* chain, including hydrogen production, storage, and development of fuel cell vehicles to meet varying end-user needs. This increased investment fosters innovation, leading to advancements in the efficiency and cost effectiveness of hydrogen-related technologies. As the HRS network grows, economies of scale are achieved, driving down investment costs, and making hydrogen-powered mobility options more accessible to consumers and businesses. As the HRS network becomes more widespread and widely available, it has the potential to create a positive feedback loop for higher fuel cell vehicle adoption. Increased availability of refueling stations encourages more consumers and businesses to invest in hydrogen fuel cell vehicles, subsequently driving higher demand for hydrogen, and further justifying the expansion of the infrastructure network.

Envisioning a future where hydrogen fuel cell vehicles coexist with other clean energy alternatives can be a reality with the rapid deployment of HRS networks across the United States. Adoption of fuel cell vehicles to serve the various sectors of the mobility applications not only addresses the range limitations of battery electric vehicles but also provides an attractive option for heavy-duty transport, where rapid refueling and extended range are imperative for operations.

3. Key Enablers for Hydrogen Refueling Infrastructure Development

Geographic siting of new HRS as part of an integrated network is a complex process that requires careful consideration of various factors. As interest in the LCI H_2 economy grows, more investors and businesses begin exploring opportunities in the hydrogen sector, including investments in refueling infrastructure development. The development of HRS is influenced by eight key determinants and market enablers (as illustrated in Figure 3-7) that shape the decision-making process.

1. **Supportive government policies and incentives:** Supportive government policies, incentives, and regulations can be significant determinants for HRS development. Subsidies, grants, tax credits, and emissions reduction targets can create a favorable environment for investments in refueling stations and promote the adoption of fuel cell vehicles.
2. **Favorable FCEV market demand and adoption:** The level of market demand for fuel cell vehicles, and the rate of vehicle adoption, heavily influences the need for new HRS. Developers are more likely to invest in areas with higher demand and greater potential for fuel cell vehicle sales. This ensures that a significant number of potential customers have access to hydrogen refueling facilities, increasing the convenience and attractiveness of fuel cell vehicles. The spacing of refueling stations as part of the overall network is vital to ensure adequate coverage, while optimizing the cost effectiveness of development. For medium- and heavy-duty applications, such as commercial fleets and trucking, locating HRS close to fleet depots and industrial areas will enhance the practicality and economic viability of fuel cell vehicle adoption.
3. **Commitments from vehicle manufacturers:** The commitment of major automotive manufacturers to produce and market fuel cell vehicles can help build market confidence to investors and developers, as it indicates a growing hydrogen demand for mobility end users and need for HRI development and expansion.
4. **Reliability of feedstock supply:** The availability of LCI H_2 and the reliability of its supply are critical considerations. Proximity to production facilities or renewable energy sources for on-site generation can influence HRS siting decisions.
5. **Streamlined regulatory development process:** Ensuring safety and compliance with regulatory requirements is paramount in the development of HRS. Stations must adhere to strict safety standards to protect the public, station operators, and the environment. Compliance with local regulations and permitting processes is crucial for establishing refueling stations. Ensuring a smooth and efficient permitting process can help faster development of HRS. Development of safety codes and standards will require continual attention to update and improve system safety as new HRI technologies are adopted over time.

6. **Availability of land and support infrastructure:** The need for supporting infrastructure, such as utilities (water, natural gas, electricity, access roads, etc.) and the availability of land, all play crucial roles in determining viable locations for HRI development.
7. **Support for technology advancements:** Advancements in hydrogen production, storage, and dispensing technologies can significantly impact the development of HRI. Cost-effective and efficient technologies drive down operational expenses and make stations more economically viable.
8. **Collaborative partnership framework:** Collaborations with private companies, governments, and the local communities can provide essential resources, funding, expertise, and public support for HRI development.

While initial HRS siting is essential, it is equally crucial to consider the potential for future expansion and scalability of the network. Planning for scalability ensures that the network can accommodate increasing demand as fuel cell vehicle adoption grows. Public perception plays a significant role in the success of HRS network. Siting stations in areas where there is positive public perception and acceptance of LCI H_2 technologies can aid in the stations' successful operation and customer adoption. These factors play a crucial role in determining the feasibility, viability, and overall success of HRS development.

H. Current U.S. Landscape of Hydrogen Transportation, Storage, and Delivery Infrastructure

Existing hydrogen transportation, storage, and delivery infrastructure can serve as a backbone for future expansion to support the growing LCI H_2 supply and demand requirements. By leveraging and connecting to existing pipelines, storage facilities, or trucking routes, new LCI H_2 infrastructure projects can extend their reach to new regions or customers, reducing the need for building entirely new systems. Understanding today's commercially mature, tried and tested hydrogen infrastructure will help assess the readiness to safely deploy and operate a larger-scale infrastructure to support increased LCI H_2 demand in the United States.

Figure 3-7. Enablers for Hydrogen Refueling Infrastructure Development

Existing hydrogen infrastructure provides valuable insights into the design, construction, and operation of hydrogen transportation, storage, and distribution. Current infrastructure (Figure 3-8) offers a wealth of knowledge and experience in safe transport, storage, and delivery while complying with the regulatory requirements. Studying tried and tested existing hydrogen infrastructure allows for identifying best practices and areas of improvement. Understanding operational challenges and successes can help optimize the design and operation of new infrastructure, leading to cost reductions, improved efficiency, and enhanced safety measures. Existing hydrogen infrastructure in the United States provides valuable information on potential system risks and safety considerations. By analyzing operational incidents, accidents, and near-misses in the existing infrastructure, developers can identify vulnerabilities and implement measures to mitigate risks in the design and construction of new infrastructure.

As indicated in the previous section, a mature hydrogen distribution network currently operates in the United States, providing feedstock to the refining and petrochemical sectors (including ammonia and methanol). The current demand for hydrogen (produced mainly from fossil fuel feedstocks) in the United States is already significant with an end-user demand of approximately 11 MMTpa in 2021.[54] Leveraging the existing hydrogen infrastructure to transport, store, and deliver LCI H_2 could help achieve rapid emissions benefits and in a cost-effective manner. In addition to the existing hydrogen infrastructure, large-scale delivery networks exist for ammonia in the United States, primarily serving the agriculture sector and for methanol, primarily used in the chemical industry.

Understanding the current regulatory codes and standards for hydrogen transportation, storage, and delivery is important to advance the development and scaling of infrastructure to meet future hydrogen demand. This section of the chapter describes both the existing hydrogen infrastructure and regulatory landscapes.

54 Fuel Cell & Hydrogen Energy Association. 2020. "U.S. Hydrogen Road Map." https://www.fchea.org/us-hydrogen-study.

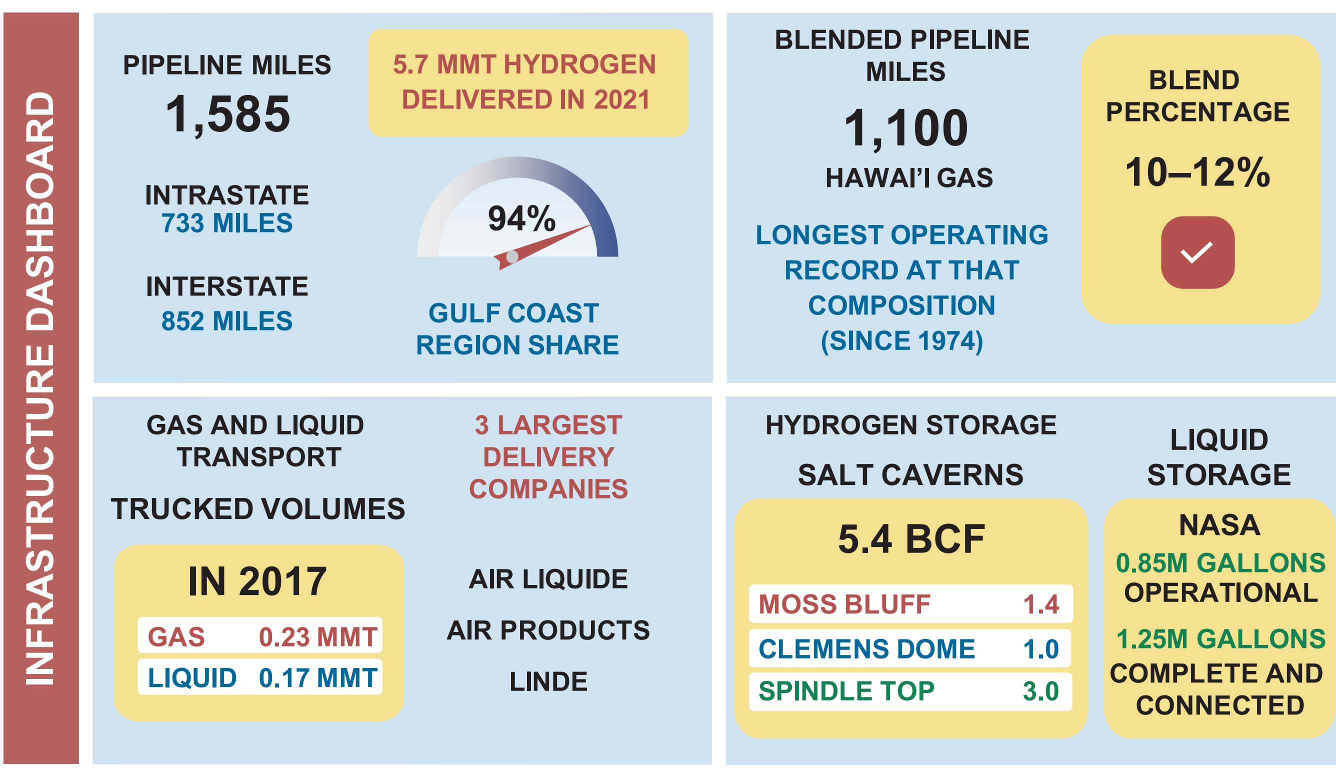


Figure 3-8. Current Hydrogen Infrastructure

1. Existing Bulk Distribution Volumes and Channels for Hydrogen, Ammonia, and Methanol

Hydrogen: Current U.S. hydrogen demand is used primarily in refining (55%) for hydrotreating conventional transportation fuels and the production of ammonia and methanol (35%) accounting for 90% of demand. Most current production is sourced from natural gas and other fossil fuels.

Hydrogen production in the United States can be broadly classified into three categories: Merchant hydrogen generated on-site or in a central production facility and sold to consumers; captive hydrogen produced by consumers for internal use; and byproduct hydrogen—recovered from byproduct process streams. High transportation costs make on-site captive hydrogen production and consumption attractive where volumetric demand is high and distribution infrastructure is limited. Merchant producers use one of three transportation modes to reach industrial end users: compressed gas through pipelines, truck deliveries of hydrogen gas in canisters, and truck deliveries of liquid hydrogen in cryogenic canisters or tanks. Hydrogen in the United States is rarely (if ever) delivered by rail or barge since neither mode has proven cost effective for current applications.

Ammonia: According to the U.S. Geological Survey (USGS) 2022 Mineral Commodity Survey, world ammonia output in 2021 was 150 MMTpa, of which 14 MMTpa (9.3 %) was produced in the United States. Net imports of 2 MMTpa imply U.S. demand was 16 MMTpa.[55] Ammonia was produced by 16 companies at 35 plants in 16 states in the United States during 2021. About 60% of total U.S. ammonia production capacity is in Louisiana, Oklahoma, and Texas due to their large reserves of natural gas, the dominant domestic feedstock for ammonia. Approximately 88% of apparent domestic ammonia consumption was for fertilizer use, including anhydrous ammonia for direct application, urea, ammonium nitrates, ammonium phosphates, and other nitrogen compounds. Ammonia also was used to produce explosives, plastics, synthetic fibers and resins, and numerous other chemical compounds.[56]

Most U.S. ammonia production is upgraded to urea and other fertilizer products, leaving approximately 7.25 MMTpa of anhydrous ammonia product to physically move through the distribution network in 2021 according to industry sources. Of this, more than half (about 3.75 MMTpa) is estimated to be for agricultural use. Most shipments begin by barge or rail with final distribution by truck. Industrial demand in 2021 was estimated at 3.5 MMTpa. Most of that moves by vessel-to-pipeline-to-plant and plant-to-plant by rail, with the rest completing its journey by truck.

There is only one ammonia pipeline in the United States: the NuStar-owned-and-operated 2,000-mile ammonia pipeline system. This common carrier pipeline was completed in 1971 and consists of 4", 6", 8", and 10"-diameter pipelines transporting liquid state anhydrous ammonia for third parties (from Louisiana and other Gulf Coast injection points) to the Midwest farm belt.[57]

Methanol: U.S. methanol production capacity was estimated by Argus Media to be more than 10 MMTpa in 2021, with demand at 7 MMTpa and the balance exported.[58] The world's largest producer, Methanex, estimated global demand was 86 MMTpa in 2021.[59] According to Methanex, more than 50% of methanol production is used to produce formaldehyde, acetic acid, and other chemical derivatives. The remaining demand comes from petrochemical plants in China that convert methanol to olefins, and transport fuel components (Methyl Tert-Butyl Ether (MTBE), Dimethyl ether (DME) and gasoline blends).

55 U.S. Geological Survey. 2022. "Mineral Commodity Summaries 2022." https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-nitrogen.pdf.

56 U.S. Geological Survey. 2022. "Mineral Commodity Summaries 2022." https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-nitrogen.pdf.

57 NuStar Energy. 2021. "Pipeline Transportation of Ammonia–Helping to Bridge the Gap to a Carbon Free Future."

58 McGinn, Steven. 2021. "Viewpoint: U.S. Methanol Supply Surplus to Persist." https://www.argusmedia.com/en/news-and-insights/latest-market-news/2286228-viewpoint-us-methanol-supply-surplus-to-persist.

59 Methanex Corporation. 2022. "Methanex Corporation Annual Information Form." https://www.methanex.com/sites/default/files/investor/annual-reports/269862_Methanex_2021AIF_March10.pdf.

Most U.S. methanol plants are in the Gulf Coast region.[60] Some are connected by pipeline to export dock facilities from where methanol is shipped worldwide in standard chemical tankers. Imports are received and stored at marine terminals. Methanol is shipped by barge between the Texas and Louisiana Gulf Coasts, as well as up the Mississippi River to discharge points throughout the Midwest. Typical methanol barges are 10,000 barrels in volume. Inland movements otherwise use railcars and tanker trucks. Rail is the most economic option for distances more than 250 miles. Rail cars are most often 600 barrels, while the capacity of a tanker truck is about 200 barrels.[61]

Methanol is widely used in China as an alternative to gasoline and was once considered a viable substitute in the United States. A network of more than 100 methanol gas stations was built in California during the 1990s. For transportation and storage, methanol has similar characteristics to gasoline and ethanol. An expansion of methanol production and distribution for use as a hydrogen carrier wouldn't therefore require significant bulk infrastructure innovation.

I. Overview of Existing Bulk Hydrogen Distribution

1. Compressed Gas Pipelines

Compressed hydrogen volumes shipped by pipeline in 2021 were estimated at 5.7 MMTpa by PHMSA, based on annual reporting data.[62] Most pipelines are in the Gulf Coast region (but a small number are in California) and are intrastate (Figure 3-9). Shipment volume on interstate pipelines between Texas and Louisiana was estimated by PHMSA at 1.6 MMTpa in 2021.

According to PHMSA's annual gas transmission and gathering statistics, 1,585 miles of gaseous hydrogen pipeline operated in the United States during 2022. Most of these pipelines (94%) are in Texas (1,018 miles) and Louisiana (477 miles), with a few being interstate systems stretching across both Gulf Coast states. PHMSA's records identify a total of 25 hydrogen pipeline operators in the United States. Nine companies operate 97% of the existing network (1,535 miles). Of those companies, Air Products, Linde, and Air Liquide operate close to 90% (1,421 miles) between them (see Appendix L: List of Hydrogen Pipeline Operators in the United States, Table 3-8).

Hydrogen pipelines are mainly concentrated at the Gulf Coast where they connect large clusters of oil refineries, petrochemical and hydrogen production plants in the region. Refineries consume hydrogen primarily as a feedstock, while bulk petrochemical plants (mostly ethylene crackers) produce byproduct hydrogen. The 2021 Energy Information Administration (EIA) annual refining survey shows 54% of the nation's refining capacity is in the Gulf Coast region. There's an even greater concentration of bulk petrochemicals in the region, with 95% of U.S. ethylene cracker capacity located in Texas and Louisiana.[63]

The resulting market for consistent, long-term hydrogen supply and offtake has enabled the buildout of long-distance transmission pipelines in the region by the three largest operators. Air Liquide has an extensive industrial gas pipeline system, spanning nearly 2,000 miles, supplying oxygen, nitrogen, and hydrogen to customers along the Gulf Coast in Texas and Louisiana. Air Products operates an approximately 700-mile pipeline from Texas City, Texas, to New Orleans, Louisiana, that links together 25 production plants and can supply customers with 1.6 MMTpa of gaseous hydrogen.[64] Linde, through U.S.-based subsidiary Praxair, operates the 375-mile

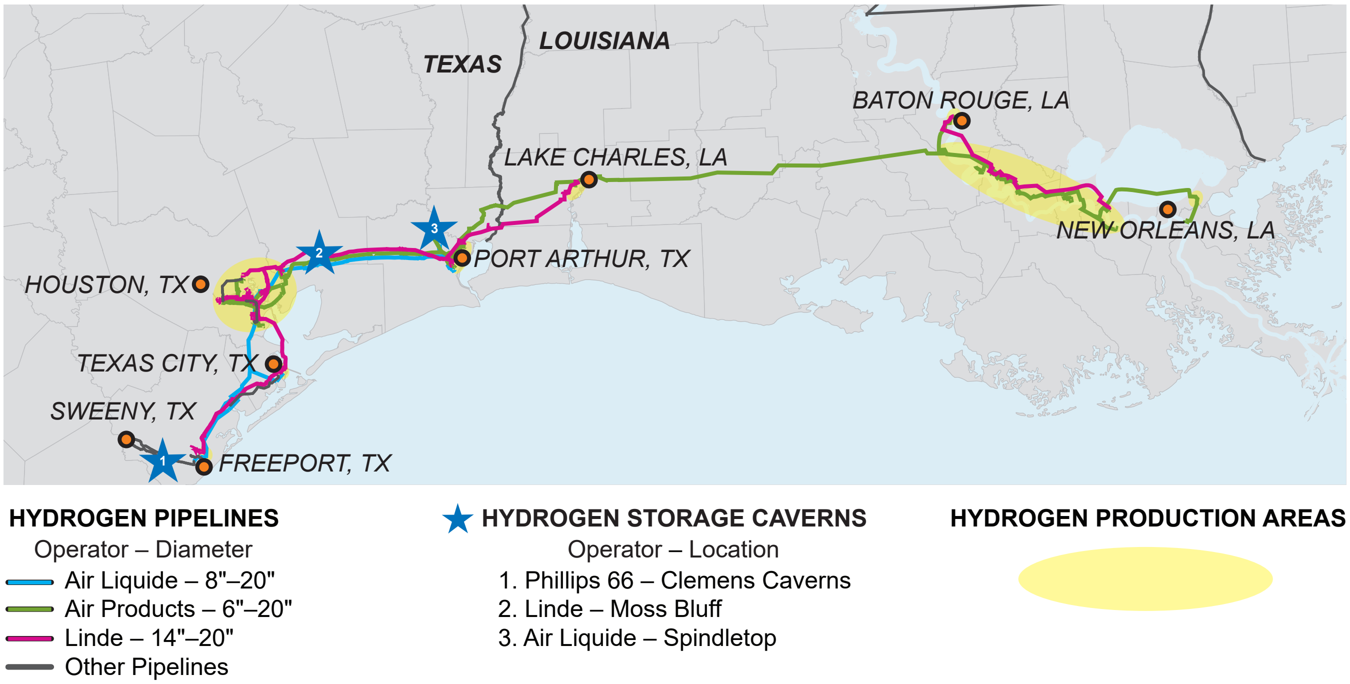
60 EIA. 2019. "New Methanol Plants Expected to Increase Industrial Natural Gas Use Through 2020." https://www.eia.gov/todayinenergy/detail.php?id=38412#:~:text=Most%20methanol%20plants%20are%20located.

61 DOE. 2008. "Final Report: Hydrogen Delivery Infrastructure Options Analysis." https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/delivery_infrastructure_analysis.pdf.

62 U.S. Census Bureau. 2021. "2017 Commodity Flow Survey Datasets: 2017 CFS Public Use File (PUF)." https://www.census.gov/data/datasets/2017/econ/cfs/historical-datasets.html.

63 DOE. 2018. "Ethane Storage and Distribution Hub in the United States." https://www.energy.gov/sites/prod/files/2018/12/f58/Nov%202018%20DOE%20Ethane%20Hub%20Report.pdf.

64 Air Products. 2020. "Air Products to Make Largest-Ever U.S. Investment of $500 Million to Build, Own, and Operate Its Largest-Ever Hydrogen SMR, a Nitrogen ASU and Utilities Facilities, and Wins Long-Term Contract to Supply Gulf Coast Ammonia's New World-Scale Texas Production Plant." https://www.airproducts.com/company/news-center/2020/01/0108-air-products-to-build-its-largest-smr-to-supply-gulf-coast-ammonia.



Source: RBN Energy Internal Report, 2023.

Figure 3-9. *U. S. Gulf Coast Hydrogen Infrastructure*

Gulf Coast Pipeline from Sweeny, Texas, to Lake Charles, Louisiana. Linde's Gulf Coast distribution network also includes a pipeline connecting Baton Rouge and New Orleans in Louisiana. Together, Linde's pipelines can supply more than 1.3 MMTpa of hydrogen. Customers supplied by these long-distance pipelines are generally tied to multiyear supply contracts with penalties for not meeting minimum offtake commitments. The pipelines are bidirectional in places and take inputs from production plants as well as commercial sources (multiple propane dehydrogenation plants in Mont Belvieu, Texas).

According to PHMSA, about 70% of hydrogen pipelines were built between 1980 and 2010, with only 55 miles added between 2010 and 2020. Most pipelines were reported as between 8 and 18 inches in diameter, and almost all are constructed of cathodically protected coated steel. Hydrogen pipeline pressures are in a range between 28 and 138 bar, with the majority operating between 41 and 62 bar.[65]

2. Hydrogen Blending with Natural Gas

Although not widely practiced in the Lower 48, the existing pipeline network of Hawai'i Gas currently accommodates a blend of synthetic natural gas (SNG), renewable natural gas, and up to 15% hydrogen. That is more utility hydrogen than any other local distribution company in the United States.[66] The hydrogen gas blend is distributed to Oahu utility customers through 1,100 miles of transportation pipeline with operating pressures less than 50% of the pipeline's specified minimum yield strength and a delivery pipeline network that was constructed and maintained over the past 100+ years.[67]

3. Truck Delivery of Gaseous and Liquid Hydrogen

Published estimates of hydrogen shipments by truck are less reliable than for pipelines since

65 DOE. 2008. "Final Report: Hydrogen Delivery Infrastructure Options Analysis." https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/delivery_infrastructure_analysis.pdf.

66 Hawai'i Gas. n.d. "Decarbonization and Energy Innovation." https://www.hawaiigas.com/clean-energy/decarbonization.

67 Hawai'i Gas. 2023. "Request for Proposals: Supply of Renewable natural Gas and Renewable Hydrogen" https://assets-global.website-files.com/618c69307382fa36b31ac896/642e9d0fdaa00c9579970c3b_Hawaii%20Gas%20Renewable%20Natural%20Gas%20and%20Renewable%20Hydrogen%20RFP%20FINAL%204-6-23.pdf.

reporting is not required. The U.S. Department of Transportation (DOT) and U.S. Customs five yearly commodity flow survey (CFS) tallies individual movements of hydrogen and other hazardous materials like ammonia, but the estimates are based on survey responses that only cover a subset of journeys, and commercial sensitivity reduces the data published for highly specialized liquid hydrogen transportation. The latest CFS for 2017 indicates 0.23 MMTpa of hydrogen gas and 0.17 MMTpa of liquid hydrogen were shipped by truck that year, accounting for only about 4% of U.S. hydrogen production.[68]

Substantial infrastructure exists to deliver smaller quantities of hydrogen as well as other industrial gases to a wide base of merchant and package customers across the United States. The three largest suppliers are the same as for pipeline gas: Air Liquide, Air Products, and Linde. Each company has a proprietary distribution network with a combination of liquid and compressed gas facilities servicing truck deliveries.

Customers are supplied based on volume requirements, with larger consumers encouraged to host small-scale, on-site hydrogen production plants to ensure secure supply. Hydrogen deliveries are scaled to match customer needs with transport economics. Larger volumes are delivered in liquid form by tanker trucks over distances up to 250 miles. Smaller volumes are delivered by gas tube trailers in canisters over distances that are less than 50 miles. Volumes delivered by gaseous tube trailer depend on canister pressure and the number of tubes, with a typical load of 140 kg – 300 kg at a pressure of 167 bar. Higher canister pressures allow higher volumes but require thicker casings. There is a DOT limit of 250 bar, above which a special permit is required.[69]

The merchant market is well developed with suppliers meeting industrial gas needs from industries as diverse as automotive manufacturing, technology, food, and retail. Air Liquide's U.S. subsidiary, Airgas, boasts 900 branches across the country.[70] This merchant supply network has proven capable in supplying new mobility applications, such as 58 HRS operating in California[71] and 50,000 hydrogen fuel cell forklift trucks in use across the nation.[72] Large U.S.-based supplier Plug Power provides fuel cells and hydrogen support services for over 12,000 forklift trucks used for material handling by retailers like Amazon and Walmart. Truck manufacturer Nikola Corp. commenced work in February 2023 on a network of hydrogen plant and storage infrastructure to supply enough fuel for 7,500 heavy-duty hydrogen fuel cell-powered trucks by 2026 in parts of the United States and Canada.[73]

4. Existing Storage Infrastructure for Hydrogen, Ammonia, and Methanol

Bulk hydrogen storage buffers producers and consumers against supply and demand fluctuations. Commercial bulk hydrogen storage facilities operating in the United States today take one of two forms: compressed gas in underground salt caverns, and liquid hydrogen stored in aboveground structures. Nonbulk quantities of gaseous hydrogen are stored in a myriad of different cylinder sizes and configurations throughout the merchant distribution network, but they can provide only minimal protection against supply disruption due to volume and cost constraints.

Liquid hydrogen is the most used buffer in the distribution network due to its compactness compared to gas. However, bulk gas storage has operated successfully for more than 30 years in underground salt caverns on the Gulf Coast, where it plays a vital role in balancing hydrogen transmission pipelines.

68 U.S. Census Bureau, 2021.

69 DOE. https://www.energy.gov/eere/fuelcells/hydrogen-tube-trailers.

70 Air Liquide. 2017. "Airgas Site Visit Multi-Channel Distribution Network Presentation." https://www.airliquide.com/sites/airliquide.com/files/2022-01/air-liquide-2017-multi-channel-distribution-network.pdf.

71 Hydrogen Fuel Cell Partnership. 2024. "By the Numbers: FCEV Sales, FCEB, & Hydrogen Station Data." https://h2fcp.org/by_the_numbers.

72 Congressional Research Service. 2023. "Hydrogen Hubs and Demonstrating the Hydrogen Energy Value Chain." https://crsreports.congress.gov/product/pdf/R/R47289.

73 Tita, Bob. 2023. "Nikola Constructs Hydrogen Fuel Network to Power Zero-Emissions Trucks," *The Wall Street Journal*. February 11, 2023. https://www.wsj .com/articles/nikola-constructs-hydrogen-fuel-network-to-power-zero-emissions-trucks-29634212#comments_sector.

a. Bulk Hydrogen Gaseous Storage

The three underground salt cavern storage facilities currently operating in the United States are in Texas as shown in Figure 3-10.

The oldest, at Clemens Dome, has been operating since 1986 and is currently owned by the Chevron-Phillips 66 joint venture, Chevron-Phillips Chemical. Clemens Dome has 1.0 Bcf of working storage capacity (approximately 2,000 MT). The Linde cavern at Moss Bluff, built by Praxair and operating since 2007, has 1.4 Bcf of working storage capacity. The Air Liquide Spindletop cavern is the newest and largest with 3.0 Bcf of working storage capacity, in operation since 2017. Table 3-2 summarizes storage capacity and operating characteristics of these storage caverns.

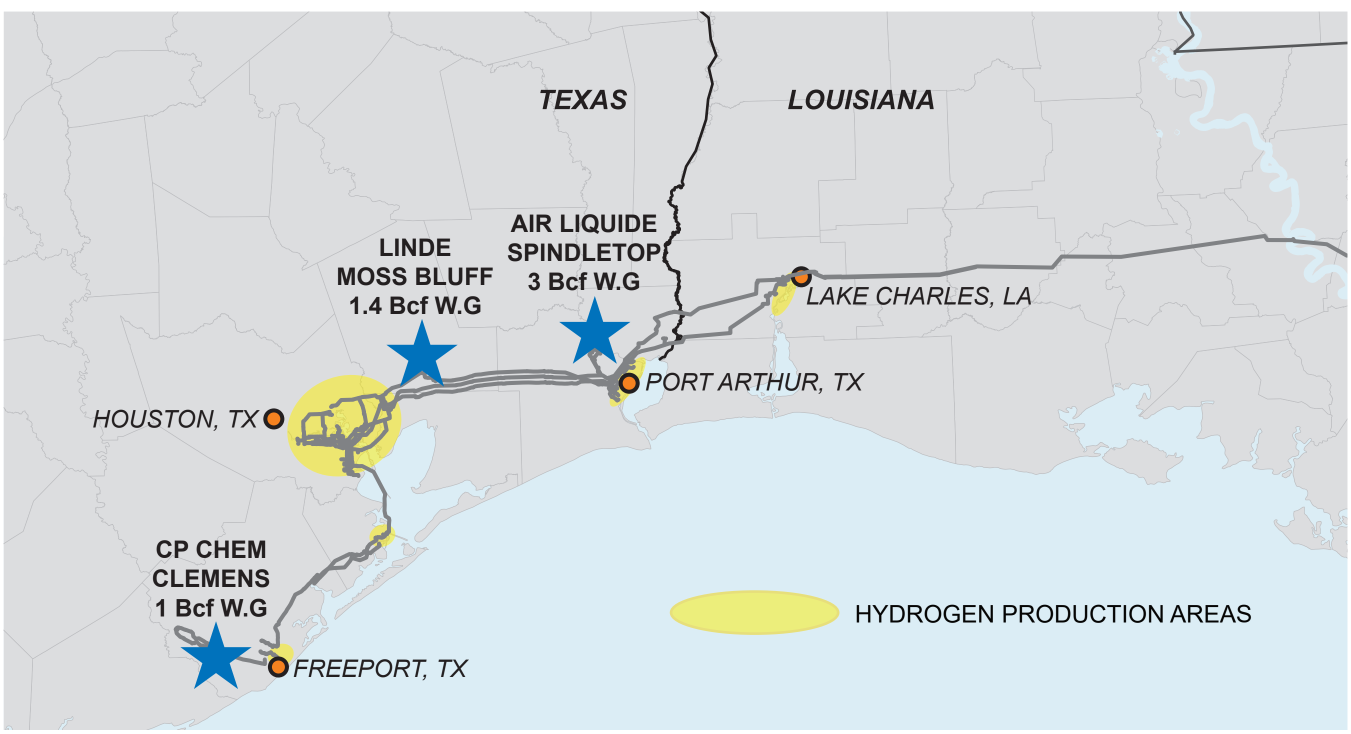
Both Linde and Air Liquide storage caverns are integrated closely with their hydrogen pipeline networks serving refineries and chemical plants in Texas and Louisiana. Linde attributes the value of its storage cavern to allowing hydrogen production plants to be brought on- and off-line without large inefficiencies and keeping refineries running when their on-site production is disrupted.[74]

Bulk hydrogen liquid storage: On-site storage provides essential buffering for merchant customers supplied with liquid hydrogen. Air Liquide estimated that the company had installed about 53,000 cryogenic tanks at client sites worldwide by 2021.[75] The systems that are used, owned, and installed by suppliers, consist of a tank, vaporizer, and controls. Tanks are usually cylindrical in shape and placed in a horizontal position. Some vertical and spherical tanks are also in use. Standard tank sizes range from 1,500 gallons to 25,000 gallons.[76] On-site tanks are refilled from liquid hydrogen semi-trailers.

74 Linde. 2022. "Increase Hydrogen Supply Availability with Cavern Storage." https://www.lindehydrogen.com/-/media/corporate/linde-hydrogen/files/brochures_downloads/expert-insights-2022-hydrogen-supply-in-caverns.pdf.

75 Air Liquide. 2021. https://www.airliquide.com/sites/airliquide.com/files/2022-03/air-liquide-2021-universal-registration-document.pdf.

76 Air Products. 2019. "U.S. Liquid Hydrogen Safetygram 7." https://www.airproducts.com/company/sustainability/safetygrams.



Source: RBN Energy Internal Report, 2023.

Figure 3-10. Texas Hydrogen Salt Cavern Storage

Location	Depth (Meters)	Start Year	Purity Level %	Operating Pressure (bar)	Working Capacity (BCF)
Moss Bluff	850–1,400	2007	N/A	70–135	1.4
Clemens Dome	850	1986	95	150	1.0
Spindle Top	850–1,400	2017	95	Up to 150	3.0

Source: Gaffney Cline, "Underground Hydrogen Storage," 2022.

***Table 3-2.** Existing Salt Caverns in the United States*

NASA liquid hydrogen storage: The world's largest liquid hydrogen storage tanks are aboveground spheres constructed in the mid-1960s at the NASA Kennedy Space Center in Florida by Chicago Bridge and Iron. These tanks, one of which remains in service, have a maximum capacity of 850,000 gallons, an outer diameter of 69 feet, and double-walled, 4-feet-thick perlite bulk filled insulation.[77] They were built to supply liquid hydrogen fuel for the Apollo space program and were also used for the Space Shuttle. NASA purchased bulk liquid hydrogen from two suppliers—an Air Products plant in New Orleans, LA, and a Linde (Praxair) plant in McIntosh, IL. Supplies are delivered by semi-truck tankers carrying up to 15,000 gallons.[78] A new, larger liquid hydrogen storage sphere, with 1.25-million-gallon usable capacity was recently built at the Kennedy Space Center to support the Artemis program. The new tank has an integrated refrigeration and storage heat exchanger that reduces boil-off (about 50% lower) with the more efficient glass bubble thermal insulation system.[79]

Ammonia bulk storage: Ammonia bulk storage infrastructure in the United States is mature due to widespread use as a feedstock for inorganic fertilizers. The USGS 2022 Commodity Summary estimated year-end 2021 ammonia inventory at 360,000 MT.[80] According to the Fertilizer Institute, approximately 3,800 agricultural retail facilities across the United States stored or handled anhydrous ammonia in 2015.[81] At room temperature and atmospheric pressure, ammonia is a colorless, pungent gas. To store in bulk, it requires liquefaction either by compression to 10 times atmospheric pressure or chilling to -33°C (-27.4°F). The most common storage tanks are refrigerated and insulated to store ammonia at atmospheric pressure. The main types of tanks operating are either single wall steel with external insulation or double wall steel with perlite insulation between the walls. Tank sizes vary with need, but the largest are located at ports where ammonia is produced for export. The world's largest are two 50,000 MT refrigerated ammonia tanks in Doha, Qatar, owned by the Qatar Fertilizer Company.

Methanol bulk storage: Methanol can be stored in mild steel tanks, which are commonly used throughout the United States. Dedicated methanol storage tanks are already in service, and most major ports and terminal locations have ample room for expansion of existing facilities. Storage of methanol is subject to substantially the same provisions as those used for gasoline. Methanol is routinely stored in tank farms consisting of aboveground, floating roof tanks and smaller, internally baffled fixed roof tanks.[82]

77 Fesmire, James E., and Adam Swanger. 2021. "Overview of the New LH_2 Sphere at NASA Kennedy Space Center." https://ntrs.nasa.gov/citations/20210020920.

78 DOE. 2020. "H_2IQ Hour: Cold and Cryo-Compressed Hydrogen Storage R&D and Applications." https://www.energy.gov/eere/fuelcells/downloads/h2iq-hour-cold-and-cryo-compressed-hydrogen-storage-rd-and-applications.

79 Fesmire, James E., and Adam Swanger. 2021. "Overview of the New LH_2 Sphere at NASA Kennedy Space Center." https://ntrs.nasa.gov/citations/20210020920.

80 U.S. Geological Survey. 2022. "Mineral Commodity Summaries 2022." https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-nitrogen.pdf.

81 IFCA. 2016. "The Fertilizer Institute Applauds Senators' Introduction of the FARM Act, Fertilizer Institute." Accessed September 20, 2023. https://www.ifca.com/resource_display/?id=2046&title=The+Fertilizer+Institute+applauds+senators+introduction+of+the+FARM+Act.

82 Methanol Institute. 2020. "Methanol Safe Handling Manual, 5th Edition." https://www.methanol.org/wp-content/uploads/2020/03/Safe-Handling-Manual_5th-Edition_Final.pdf.

J. Existing Regulations for Hydrogen Transportation and Storage

Existing bulk hydrogen transportation infrastructure is subject to considerable federal agency regulation that is summarized in this section. Currently, these regulations mostly concern safe movement and storage of hazardous materials, including gaseous and liquid hydrogen, that apply to all such materials transported within the United States. Existing regulations concerning safety of hydrogen transportation should be able to accommodate expansion of the hydrogen transportation network, though ongoing research into hydrogen's effects on pipeline integrity may inform future regulatory initiatives. In addition to federal oversight, state and local authorities have regulations in their own jurisdictions that are usually complementary to federal safety concerns, but permitting and safety concerns vary widely. Currently, it is uncertain which, if any, federal agency has jurisdiction over the siting, construction, and terms of commercial service of interstate hydrogen pipelines.

1. Hydrogen Pipeline Regulation

Onshore hydrogen pipeline regulation at the federal and state levels addresses three categories of concern: siting and construction, safe operation, and commercial terms of service. These are summarized in this section as well as distinctions between interstate and intrastate pipelines. There are no offshore hydrogen pipelines at present in the United States but, if built, they would be subject to regulation by multiple agencies.

Safety standards: The Natural Gas Pipeline Safety Act of 1968 and the Hazardous Liquid Pipeline Act of 1979 give the DOT primary authority to regulate the safety of interstate and intrastate energy commodity pipelines, including design, construction, operation, maintenance, and reporting. This authority is administered by the DOT PHMSA. Title 49 Code of Federal Regulations (CFR) Part 192 prescribes[83] minimum safety requirements for pipeline facilities and the transportation of natural gas (including other flammable gases). Title 49 CFR 195 prescribes[84] safety standards for pipeline facilities that transport hazardous liquids, including supercritical CO_2, and hydrogen carriers ammonia and methanol.

Via its Office of Pipeline Safety (OPS), PHMSA ensures requirements in these federal regulations are met for the design, construction, and operation of hydrogen pipelines. Oversight by OPS is direct for interstate pipelines, including inspections and annual reporting. OPS also provides oversight of PHMSA regulation for intrastate pipelines but can delegate that responsibility to the states by agreement with PHMSA.

Uncertainty in regulatory authority: PHMSA has authority over pipeline design and construction, operation and maintenance, and emergency response planning, but not the routing, location, or environmental impacts of the pipeline construction activities. It is uncertain which, if any, federal agency has jurisdiction over interstate hydrogen pipelines' siting, rates, or services.[85, 86] Three different federal statutes provide for economic regulation of different types of pipelines: 1) the Natural Gas Act, which requires the FERC to regulate the interstate transportation of natural gas; 2) the Interstate Commerce Act, which requires FERC to regulate the interstate transportation of oil; and 3) the Interstate Commerce Clause Termination Act, which requires the Surface Transportation Board to regulate the interstate transportation of "a commodity other than water, gas, or oil." See Chapter 6: Policy for additional details on the authority of hydrogen pipeline regulations.

Siting and construction: Individual states regulate siting and construction within their borders

83 DOT PHMSA. 2021. "Pipeline Safety: Pipeline Regulatory Reform." *Federal Register*. 86 FR 2210. https://www.federalregister.gov/documents/2021/01/11/2021-00208/pipeline-safety-gas-pipeline-regulatory-reform.

84 DOT PHMSA. 2019. "49 CFR Part 195 Pipeline Safety: Safety of Hazardous Liquid Pipelines." *Federal Register*. 84 FR 52260. https://www.federalregister.gov/documents/2019/10/01/2019-20458/pipeline-safety-safety-of-hazardous-liquid-pipelines.

85 U.S. Senate Committee on Energy and Natural Resources. 2022. "Full Committee Hearing on Federal Hydrogen Pipeline Regulatory Authorities." https://www.energy.senate.gov/hearings/2022/7/full-committee-hearing-on-federal-hydrogen-pipeline-regulatory-authorities.

86 Van Ness Feldman. 2022. "Jurisdiction over Hydrogen Pipelines and Pathways to an Effective Regulatory Regime." https://www.vnf.com/Hydrogen-Pipelines.

and no federal agency has power to grant interstate hydrogen pipelines the right of eminent domain to accelerate right-of-way acquisition. Developers must seek separate approvals from every state through which the pipeline passes, each having their own requirements. Developers must also comply with any relevant federal laws, including the Endangered Species Act, the National Historic Preservation Act, the Coastal Zone Management Act, and the Clean Water Act. Requirements may include permits for water crossings from the Army Corps of Engineers, permits to cross Federal Lands from the Bureau of Land Management and any other federal approvals that require analysis of significant environmental impacts in compliance with the National Environmental Policy Act (NEPA).[87] See Chapter 6: Policy for additional details on siting of hydrogen pipelines.

Commercial terms of service: No federal agency regulates rates or terms of service for interstate hydrogen pipelines, and even in the absence of federal regulation, individual states lack authority to regulate interstate hydrogen pipelines' commercial terms of service.[88, 89, 90] Intrastate hydrogen pipelines' terms of service may be regulated by individual states, but commercial terms are currently set privately by counterparties. See Chapter 6: Policy for additional details on economic regulation of hydrogen pipelines.

2. Regulation of Hydrogen Transportation by Road

Safe road transport of hydrogen as a compressed gas in tube trailers and as a cryogenic liquid in cylinders or tankers is overseen by PHMSA through 49 CFR Subchapter C-Hazardous Materials Regulations. These regulations designate gaseous and liquid hydrogen as hazardous materials and list numerous requirements for their labeling, loading equipment, and fill rates, as well as for transportation vessel sizes, pressures, and volumes.

More broadly, the DOT Federal Highway Administration regulates highway safety, which includes bridges, tunnels, and other associated elements, and the DOT Federal Motor Carrier Safety Administration regulates motor carrier routing, safety regulations, and transportation of hazardous materials.

These safety regulations apply to road transport throughout the United States. Additional state and local road regulations also apply in specific jurisdictions.

3. Regulation of Hydrogen Transportation by Water

Regulation of gaseous or liquid hydrogen as cargo transported by water (inland or in coastal waters) depends on whether the route is on federal or state waters and what agreement state and local regulators have with federal oversight. Overall, PHMSA regulates transportation of containerized hazardous materials by water through 49 CFR Part 173. The U.S. Coast Guard specifies requirements for bulk hazardous materials transported by vessel in Titles 33 and 46 of the CFR. As with roadways, additional state and local regulations may apply within specific jurisdictions.

4. Regulation of Hydrogen Transportation by Rail

As indicated previously, minimal bulk hydrogen transportation occurs by rail in the United States due to unfavorable economics. Nevertheless, PHMSA regulations cover rail transport of hazardous materials in general, including hydrogen. Many PHMSA rail safety regulations are the same as for road and water under 49 CFR, but some are specific to rail (49 CFR Part 179) that provides construction requirements for DOT-113A60W rail tank cars designed to carry liquid hydrogen.[91]

87 Congressional Research Service. 2021. "Pipeline Transportation of Hydrogen: Regulation, Research & Policy." https://crsreports.congress.gov/product/pdf/R/R46700.

88 Library of Congress. 1924. "U.S. Reports: Missouri v. Kansas Gas Co., 265 U.S. 298 (1924)." https://www.loc.gov/item/usrep265298.

89 Library of Congress. 1927. "U.S. Reports: Public Util. Comm. V. Attleboro Co., 273 U.S. 83 (1927)." https://www.loc.gov/item/usrep273083.

90 Library of Congress. 1934. "U.S. Reports: State Comm'n v. Wichita Gas Co., 290 U.S. 561 (1934)." https://www.loc.gov/item/usrep290561.

91 DOT PHMSA. "49 CFR Part 179 Hazardous Materials: Notice of Updated Rail Tank Car Thermal Protection Systems List." *Federal Register*. 86 FR 2210. https://www.federalregister.gov/documents/2018/06/05/2018-11988/hazardous-materials-notice-of-updated-rail-tank-car-thermal-protection-systems-list.

5. Regulation of Hydrogen Storage

At the federal level, safe storage and handling of gaseous and liquid hydrogen is regulated by the Department of Labor Occupational Safety and Health Administration. Section 29 CFR Part 1910 covers the safety of structural components and operation of gaseous and liquid hydrogen storage and delivery. Storage of liquid hydrogen is also subject to Federal Aviation Administration safe distance requirements specified in 14 CFR Part 420.

Several industry codes and standards related to hydrogen storage for distribution may be adopted and enforced by states or local authorities having jurisdiction. An example is the National Fire Protection Association (NFPA) 2023 Hydrogen Technologies Code.[92] This code provides safeguards for the generation, installation, storage, piping, use, and handling of hydrogen in compressed gas or cryogenic liquid form. The codes are only recommendations but are frequently adopted by local authorities.

V. ECONOMICS OF LCI HYDROGEN TRANSPORT, STORAGE, AND DELIVERY

A. Introduction and Key Insights

The development of hydrogen infrastructure, including pipelines, storage facilities, and distribution networks will require significant upfront investment. As a result, the economics of transporting, storing, and delivering LCI H_2 will impact the growth and viability of the hydrogen economy.

Given the variety of LCI H_2 production methods and end users, multiple infrastructure solutions will be required. As such, the choice of a particular infrastructure solution will likely be driven mostly by technoeconomics and regional considerations, with federal, regional, state, and local decarbonization policies underpinning the adoption. By assessing the economics of LCI H_2 transportation, storage, and delivery, stakeholders can make informed decisions regarding infrastructure investments, operational strategies, and market deployment.

This section presents economic analyses for relevant transportation, storage, and delivery pathways. The economics insights, including levelized cost analysis, are represented in real dollar terms indexed to 2020$ and do not include the cost to produce LCI H_2 (see Chapter 2: Production and Chapter 4: Integrated Supply Chain for additional information related to the costs of LCI production). The economic analysis in this section combined with Modeling results yield the following key insights:

- Trucking is the most versatile method for delivering small quantities of hydrogen. The levelized cost to distribute hydrogen by truck, including the terminal cost, is expected to be ~$1.65/kg for CGH_2 delivery and ~$2.60/kg for LH_2 delivery at 100% capacity utilization. Early investment in trucking infrastructure may come at a higher cost due to lower utilization.
- The levelized cost of operating an LH_2 refueling station is expected to be less than that for a compressed gas refueling station, since liquid refueling stations do not require high-pressure compression. However, when costs for terminal and trucking are included, the levelized cost of liquid and compressed CGH_2 refueling infrastructure nearly reaches parity at ~$3/kg hydrogen.
- Based on favorable economics relative to other modes of transportation, pipelines are expected to be the solution of choice for delivering large volumes of hydrogen over land. Assuming a large capacity, 36-inch pipeline and transport distance of 200 miles, the levelized cost of pipeline transportation in key regions is expected to be ~$0.15/kg for the South Central, Gulf Coast, and Mountain regions, ~$0.24/kg for the West Coast region, and ~$0.49/kg for the Northeast region.
- When renewable power is used to make electrolytic hydrogen, economic analysis suggests it is more cost effective to place electrolyzers close to the power source and transport hydrogen to demand centers using pipelines than it is to transport electricity from the power source to electrolyzers located near demand centers.

92 National Fire Protection Association. 2023. "NFPA 2: Hydrogen Technologies Code." https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=2.

- Salt cavern storage is expected to be much more economical than storage in liquid hydrogen tanks or pipe farms.[93] Salt cavern storage costs are expected to be as low as \$0.36/kg hydrogen at full cavern utilization, while liquid and pipe farm storage are \$2.40/kg hydrogen and \$3.23/kg hydrogen, respectively.
- LCI H_2 production from the reforming of natural gas requires the use of CCS. The cost of storing CO_2 is expected to range from \$8 to \$12/MT CO_2, while the cost of transporting CO_2 by pipeline is expected to range from \$0.10 to \$0.33/MT CO_2-mile.

B. Economics of LCI Hydrogen Transportation, Storage, and Delivery

1. Economics of LCI Hydrogen—Delivery by Trucks

Despite relatively high costs, trucking gaseous or liquid hydrogen is the most versatile method of delivery to a distributed set of end users. The levelized cost of truck movement itself is relatively modest but substantial cost is associated with the required trucking terminal. This analysis envisions very large trucking terminals with size near the practical limit for a single facility. Capital and operating cost inputs are informed by the DOE's Hydrogen Delivery and Scenario Analysis Model[94] and input from industry participants for this study (see Appendix M: Economics of LCI Hydrogen Transportation, Storage, and Delivery). Levelized costs are estimated assuming \$50/MWh power, \$5/dge[95] truck fuel, and a round-trip delivery distance of 100 miles.

For compressed hydrogen delivery, a 60 MTpd terminal, including compression, storage, and 15 loading bays is considered. The associated truck fleet considers twice as many trailers as tractors, operating under a trailer drop and swap model. Trailers are assumed to be composite type (Type IV) with a capacity of 1 MT at 500 bar. Current federal regulations restrict tube trailer pressures to 250 bar, but exemptions have been granted for higher pressures and these high-capacity trailers are becoming more commonly used. Each loading bay can load up to four trailers per day (6-hour load time).

For liquid hydrogen delivery, a 120 MTpd terminal[96] with liquefier, storage, and six loading bays is considered. The associated truck fleet considers dedicated tractor/trailer units holding 4 MT H_2 and unloading the liquid H_2 at the delivery point. Losses due to boil-off at the terminal are considered negligible by making use of the on-site liquefier but are modeled at 5% per liquid H_2 delivery during transport and offloading.

Based on the above assumptions, the levelized cost of distribution via trucking, including the terminal cost, for a 100-mile round-trip delivery is expected to be ~\$1.65/kg for gaseous delivery and ~\$2.60/kg for liquid delivery at 100% capacity utilization. These costs assume all delivered hydrogen is consumed. Residual hydrogen returned from the customer site, especially as can be expected in the compressed gas trailer drop and swap model, would further increase the levelized cost to the customer. These residual costs will vary depending on the end user-case and what minimum pressure can be used. For CGH_2 delivery, ~50% of the levelized cost is associated with the trucking terminal with the remainder associated with the trucking itself. For LH_2 delivery, terminal costs represent ~80% of the total levelized cost. A cost breakdown summary is included in Figure 3-11.

Delivery distance impacts the cost through capex (number of trucks needed to deliver a fixed amount of hydrogen per day) and operational expenses (driver labor and fuel consumption). Since CGH_2 trucks deliver less hydrogen than LH_2 trucks, the cost of delivery increases faster with distance for the CGH_2 pathway. Delivery costs come into parity at ~\$3/kg when the average delivery distance reaches about 460 miles round trip (230 miles one way).

93 A pipe farm consists of a series of pipe segments buried at a shallow distance underground.

94 Argonne National Laboratory. 2014. "Hydrogen Delivery Infrastructure Analysis (HDSAM)." https://hdsam.es.anl.gov/.

95 dge = diesel gallon equivalent.

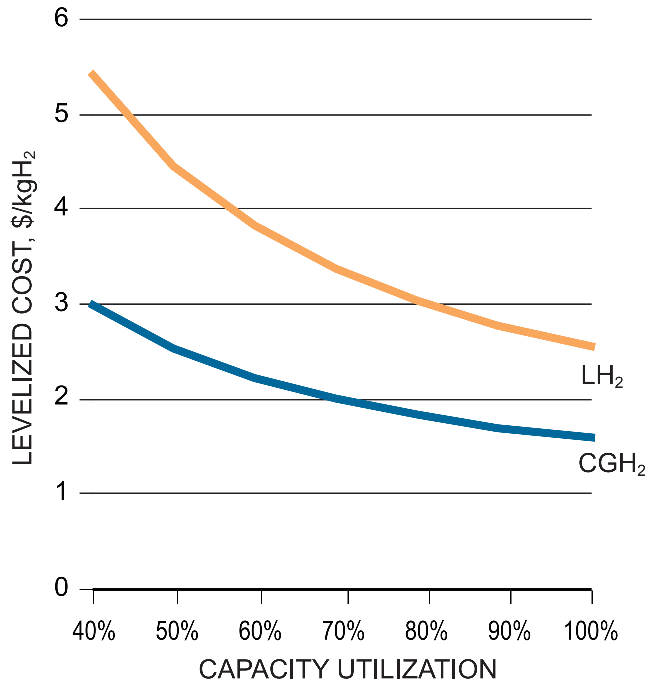
96 This capacity (120 MTpd) is approximately three times the size of current liquefaction terminals. No significant technical challenges to achieving this size are anticipated.

Delivery costs will also increase if the terminal and trucks are not fully utilized at the design (nameplate) capacity. Since fixed costs (capital, O&M) dominate, delivery costs escalate rapidly with underutilization, as shown in Figure 3-12. Costs nearly double if the utilization is less than 50%. This will be a challenge for the early stages of delivery infrastructure buildout.

2. Economics of Heavy-Duty Refueling Stations

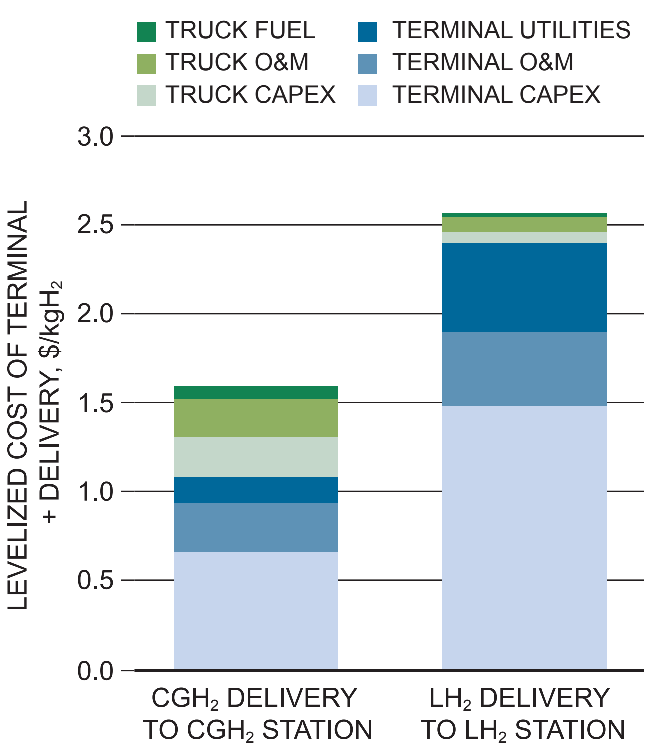
Building a hydrogen refueling station requires a significant initial capital outlay, which includes land acquisition, equipment installation, safety measures, permitting, and more. Once operational, HRS incur ongoing operating expenses, including facility operations and maintenance, staffing, and safety compliance measures. Station utilization is also a key economic driver. Government incentives, grants, and subsidies are expected to play a significant role in the development of HRS for the foreseeable future. Understanding and navigating these incentives is critical to project economics for refueling station development. With eventual increased deployment of FCEV vehicles across light-, medium-, and heavy-duty sectors, it is expected that in NZ2050 scenario, the refueling station infrastructure will be built out along major road network corridors in the United States.

This section of the chapter evaluates the economics of heavy-duty truck refueling stations serving FCEV long haul trucks. The economic assumptions for the HRS are primarily informed by Argonne National Lab's Heavy-Duty Refueling Station Analysis Model.[97] The study also assumes that larger capacity HRS (5–15 MTpd) will be required to support the heavy-duty FCEV trucking sector. The refueling station dispensers are assumed to deliver an average of 50 kg hydrogen per fill at a dispensing rate of 3.6 kgH_2/min. CGH_2 stations include gas storage and dispensers fed by a cascade compressor system to fill



Assumes: $50/MWh electricity, $5/dge truck fuel, and 100-mile roundtrip delivery distance.

Figure 3-12. Truck Delivery Infrastructure Levelized Cost as a Function of Capacity Utilization



Note: Assumes nameplate capacity, $50/MWh electricity, $5/dge truck fuel, and 100-mile roundtrip delivery distance.

Figure 3-11. Levelized Cost of Truck Distribution

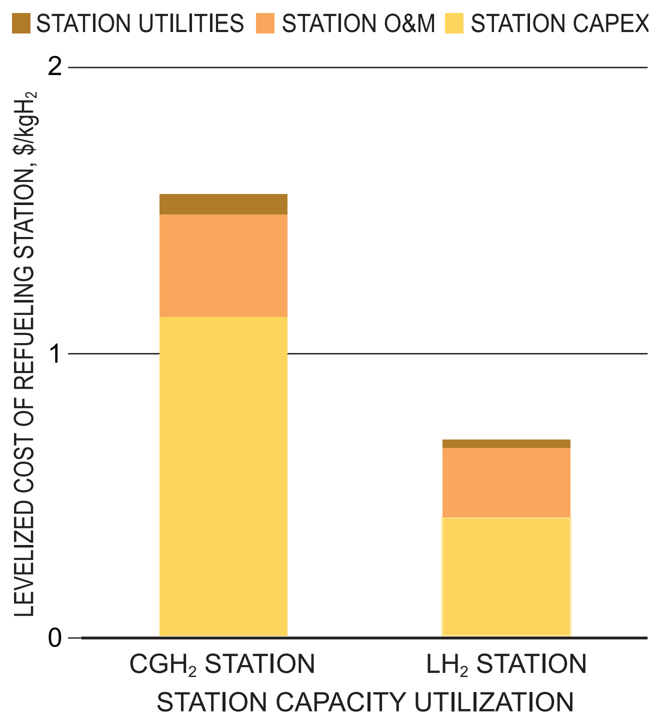
97 Argonne National Lab. 2017. "Heavy-Duty Refueling Station Analysis Model (HDRSAM)." https://hdsam.es.anl.gov/index.php?content=hdrsam.

700 bar CGH_2 vehicle tanks. Hydrogen is supplied to stations by CGH_2 tube trailer deliveries. LH_2 stations include liquid storage and dispensers fed by a liquid pump and vaporization system to fill 700 bar CGH_2 vehicle tanks; hydrogen is supplied to stations by LH_2 trailer deliveries. The analysis evaluated the refueling station cost economics across station utilization rates from 40% to 100% (see Appendix M: Economics of LCI Hydrogen Transportation, Storage, and Delivery, Table 3-14).

Gaseous and liquid hydrogen refueling station economics: The levelized cost of heavy-duty HRS is an essential metric for evaluating the economic viability of these infrastructure investments. It helps stakeholders, including investors, policymakers, and station operators, make informed decisions about building, operating, and supporting the growth of HRS in the context of heavy-duty applications, such as fueling heavy-duty trucks and buses.

The choice to offer CGH_2 or LH_2 at heavy-duty HRS depends on various factors, including initial capital investment, ongoing operating costs, station utility expenses, and the specific refueling needs of the target market. From a levelized cost perspective, it is evident from Figure 3-13 that LH_2 refueling stations show more favorable cost advantage than CGH_2 refueling stations at this scale. The difference in levelized cost is primarily driven by the need for a high-pressure gas compressor at the CGH_2 refueling station. This contrasts with the LH_2 station, which utilizes a cryogenic pump to boost the pressure of the hydrogen. High-pressure gas compression results in higher capital, maintenance, and utility costs than cryogenic pumping. To a lesser extent, the difference in levelized cost is driven by the cost of storage, with pressurized gas storage having a higher capital cost than liquid storage in a tank.

Economics of hydrogen refueling station capacity utilization: The utilization (capacity factor) of HRS can significantly impact their economics based on the type of dispensed hydrogen (CGH_2 or LH_2) as shown in Figure 3-14. The capacity factor is a measure of how efficiently a station is utilized over time, specifically comparing its actual hydrogen dispensing rate to its nameplate capacity.

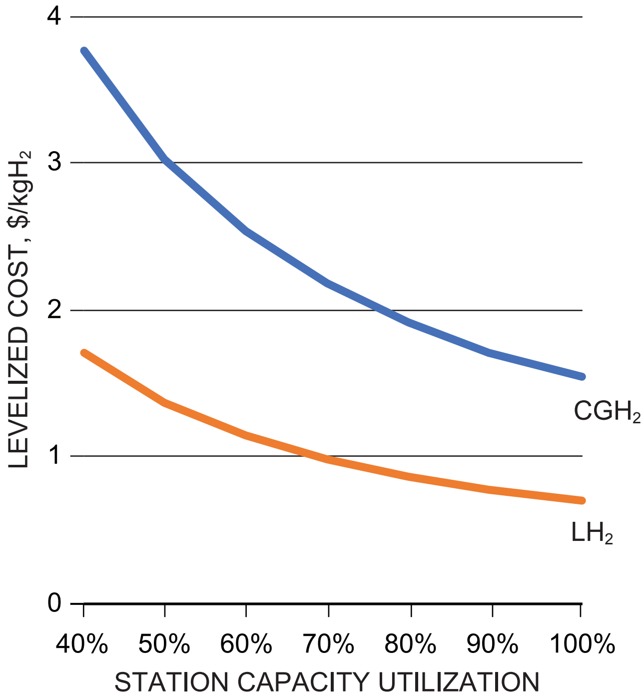


Note: Assumes nameplate capacity, $50/MWh electricity.

***Figure 3-13.** Levelized Cost of Heavy-Duty Truck Refueling Station*

Higher utilization rates reduce fixed and operating costs per unit of hydrogen dispensed, thereby lowering the levelized cost of dispensed hydrogen and making hydrogen fuel more competitive and economically viable as an alternative transportation fuel. Ensuring a high utilization of the refueling station infrastructure is essential for its economic success.

Economics of terminal, delivery, and heavy-duty station value chain: The levelized cost economics for a hydrogen refueling station itself shows relative economic advantage for liquid hydrogen when compared to compressed gas. However, when the two delivery options are compared from a levelized cost perspective across the entire supply chain (terminal, fuel delivery to station, and dispensing infrastructure), the relative advantage of liquid HRS dissipates as shown in Figure 3-15. This is due to the capital and energy costs associated with liquefying hydrogen at the terminal. For smaller volumes and shorter delivery distances, the levelized cost economics is likely to favor the compressed gas delivery option.

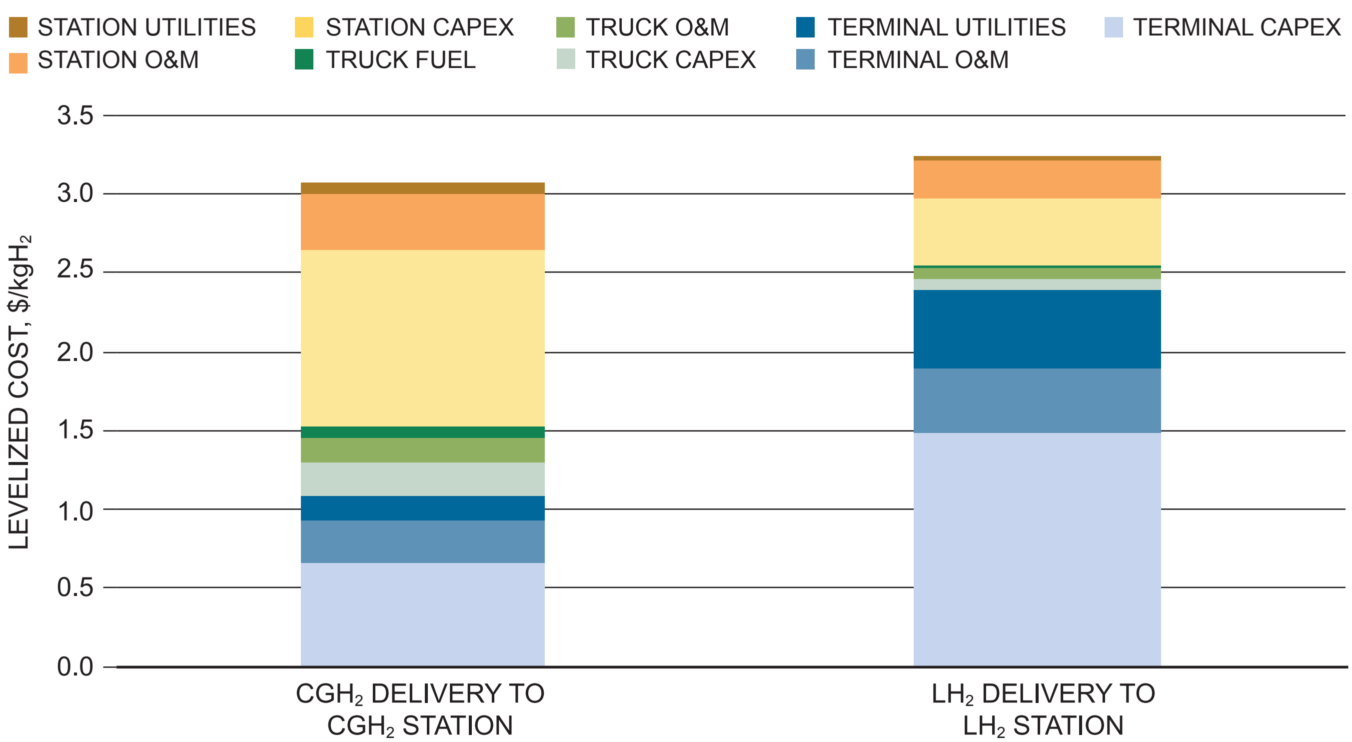


Assumes: $50/MWh electricity.

Figure 3-14. *Heavy-Duty Truck Refueling Station Levelized Cost as a Function of Capacity Utilization*

For larger volumes and longer delivery distances, the levelized cost economics is likely to approach cost parity or even favor liquid hydrogen, with liquid hydrogen having the added advantage of lower delivery traffic due to its higher energy density.

The economics of HRS play a key role in driving commercial interest and development to meet the demand of the heavy-duty FCEV market. Positive economics, including revenue from hydrogen sales, government incentives, and tax credits, will contribute to the financial feasibility of hydrogen refueling station infrastructure development. High utilization rates are essential for economic success, as stations that serve a growing number of FCEVs generate more revenue and have a better chance of recovering their capital and operating costs. Ensuring certainty of hydrogen demand and supply, efficient station operation, and competitive pricing are crucial for maintaining long-term economic sustainability and minimizing risks. By addressing economic risks proactively, developers can enhance the economic viability and long-term success of their hydrogen refueling station projects.



Notes: Assumes nameplate capacity, $50/MWh electricity, $5/dge truck fuel, and 100-mile roundtrip delivery distance.

Figure 3-15. *Levelized Cost of Terminal, Delivery, and Station Infrastructure*

3. Economics of LCI Hydrogen—Pipelines

New, purpose-built hydrogen pipelines can be constructed in a wide range of sizes for the transportation of hydrogen at varying flowrates. For this study, a nominal pipe size of 36 inches in diameter is selected to illustrate the economics for at-scale transportation of hydrogen as this line size is commonly used for new projects in the natural gas industry. Capacity and compression power requirements for a given line size depend on many variables, including operating pressure, allowable flow velocity, and compressor station spacing. This study did not develop a detailed hydraulic model, but rather relied on a work by the Transition Accelerator[98] of Canada to estimate capacity and compression power requirements[99] (see Appendix M: Economics of LCI Hydrogen Transportation, Storage, and Delivery, Table 3-10). Actual project cost data for purpose-built hydrogen pipelines is not publicly available; therefore, this study uses the project costs for natural gas pipelines as a proxy and then applies a multiplier for hydrogen service to estimate the capital cost for hydrogen pipelines. Natural gas pipeline and compression costs are based on an ICF International Inc. survey[100] of FERC project filings for a 22-year period from 2000 to 2021.[101] A 10% cost adder for hydrogen service is assumed for both pipeline and compression costs to cover enhanced pipeline welding procedures and more expensive sealing materials as compared to natural gas service.[102] No extra wall thickness is assumed for hydrogen pipelines.[103] This approach yields a U.S. average cost estimate of ~$11 million/mile for a 36-inch hydrogen pipeline (pipe only), plus ~$1 million/mile for compression capacity, for a total cost of ~$12 million/mile.

To address regional differences in hydrogen pipeline costs, the ICF survey data was mapped to the 11 U.S. regions (see Chapter 4: Integrated Supply Chain). Regions were grouped into five cost tiers (as shown in Table 3-3), characterized by the total capex relative to the estimated U.S. average (as discussed above).

Cost Tier	Region(s)	Total Capex Relative to U.S. Avg.	Total Capex M$/($tH_2$/yr)-Mi
Tier A	South, Central, Gulf Coast, Mountain	0.7	5.3
Tier B	Great Lakes	1.0	7.6
Tier C	Appalachia, Northwest, West	1.2	9.1
Tier D	Mid-Atlantic, Alaska & Hawai'i	1.5	11.4
Tier E	Northeast	2.6	19.8

Note: Regional capex to construct a 36-inch purpose-built hydrogen pipeline and associated compression in 2020 dollars.

Table 3-3. *Hydrogen Pipeline Cost Tiers Per Region*

Operating costs are categorized into fixed and variable. Fixed operating costs including labor, maintenance, etc., are estimated at $46,000 per mile annually based on FERC filings for natural gas transmission as compiled by the *Oil and Gas Journal*[104] and including a 10% adder for hydrogen service. Variable operating costs are assumed to only include power consumption for compression in the form of electricity, at the rate shown in Appendix M: Economics of LCI Hydrogen Transportation, Storage, and Delivery, Table 3-10.[105]

98 Khan, M.A., Layzell, D., and Young, C. 2021. "The Techno-Economics of Hydrogen Pipelines." https://transitionaccelerator.ca/reports/the-techno-economics-of-hydrogen-pipelines/.

99 Khan et al., 2021. The Transition Accelerator study assumes inlet pressure of 20 bar, compressor station spacing of 500 km, compressor discharge of 70 bar, and enroute compressor station inlet pressure of 28 bar. The resulting power requirement to move 4,300 MTpd of hydrogen for 1,500 km is approximately 270 MW_e, equivalent to 0.05 MWe/GWH_2-LHV-mile.

100 See Appendix N: Petak, K., Griffith, A., and Krieg, E. "Pipeline and Compression Cost Study." Prepared for National Petroleum Council. ICF (03/03/2023). https://harnessinghydrogen.npc.org/files/H_2-Appendix_N-2024-04-23.pdf.

101 ICF performed a regression analysis on the FERC project dataset to estimate pipeline and compression costs by region.

102 For comparison, the July 2020 European Hydrogen Backbone study cites a range of 110-150% for the cost of a new hydrogen pipeline as compared to a similar natural gas pipeline (See Appendix A, Table 4). The EHB study also states that the cost of 36" and larger pipelines is expected to be on the lower end of the range.

103 Kahn et al., 2021.

104 Oil and Gas Journal. 2022. "Pipeline Economics Special Report." https://www.ogj.com/magazine/62220.

105 For new hydrogen pipelines, it is assumed that compression power will be provided by electric motors connected to the electric grid.

Using a cost recovery period of 30 years, electrical power cost of $50/MWh, 100% utilization, and other assumptions consistent across the study, the levelized cost of transporting hydrogen using pipelines was developed as a function of distance, as shown in Figure 3-16.

High-capacity pipelines delivering large volumes of hydrogen currently offer the cheapest way to move hydrogen over longer distances and the potential to connect geographically separated supply and demand centers. As with trucking, however, the economics of pipeline transportation are very sensitive to utilization.

4. Economics for Long-Distance Transportation of Electrons and Molecules

In an At-Scale phase (as discussed in Section II of this chapter), the renewable power needed to produce electrolytic hydrogen may not always be located near the source of demand for the hydrogen, thus requiring the long-distance movement of energy. Two potential energy transport pathways can be envisioned to address the above challenge:

- Energy transport in the form of high-voltage electricity delivered through a power transmission network followed by electrolytic hydrogen production in proximity to end users.
- Electrolytic hydrogen production in proximity to the power source, followed by energy transport in the form of gaseous hydrogen delivered through pipelines to end users.

In addition to evaluating the levelized cost to transport hydrogen by pipeline (as discussed in Section V.B.3 of this chapter), the study also developed a cost model for electrical transmission based on the U.S. National Renewable Energy Lab's (NREL) ReEDS model[106] and informed by industry input to assess the relative comparison of the power transmission pathway. The electrical

106 Ho, J., Becker, J., Brown, M., Brown, P., Chernyakhovskiy, I., Cohen, S., and Cole, W., et al. 2021. "Regional Energy Deployment System (ReEDS) Model Documentation: Version 2020." https://www.nrel.gov/docs/fy21osti/78195.pdf.

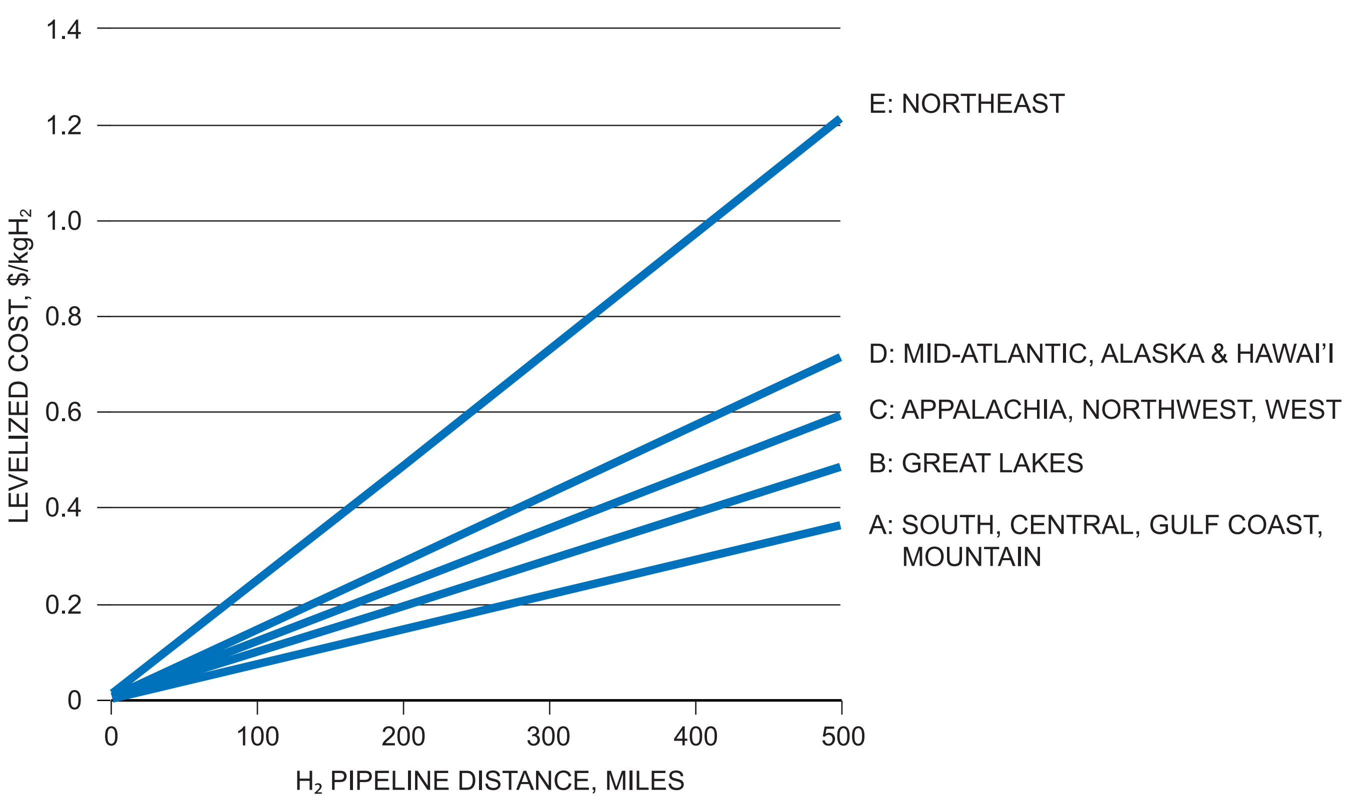


Figure 3-16. *Levelized Cost of Hydrogen Transport by Pipeline*

cost model reflects a mix of long-distance and spur-line transmission, in the form of mostly high-voltage alternating current lines and some high-voltage direct current lines. For simplicity, the cost variability between 11 U.S. regions is grouped into three tiers. See Appendix M: Economics of LCI Hydrogen Transportation, Storage, and Delivery, Table 3-11, for additional information.

Comparison between electric transmission and hydrogen pipelines was developed based on the above scope configuration assumption and cost assessment framework. The relative cost-effective comparison of the two pathways was normalized in \$/kg H_2 basis as shown in Figure 3-17. This basis is straightforward for pipelines transporting gaseous hydrogen. For electric transmission, the value reflects the cost to move the amount of electricity required to generate a kilogram of hydrogen by electrolysis.[107] The results for the Gulf Coast and West Coast regions give an indication for the range of costs across the United States.

107 Assumed electrolyzer electricity consumption is 60 MWh to produce 1 metric ton of hydrogen.

The choice of moving energy either as molecules (hydrogen) or as electrons (electricity) could be dictated by several factors, including regionality constraints, siting/land-use restrictions, environmental impacts, technoeconomics, and transporting distance. Further analysis would be needed to help understand how electricity and LCI H_2 infrastructures can be combined to create the most value for end users, and how market design and policies can enable the choice.

If the costs of electrolyzers and water are comparable at both ends and permitting is feasible for both high-voltage electricity lines and hydrogen pipelines, this comparison suggests it is more cost effective to place electrolyzers close to the power source and transport hydrogen to demand centers using pipelines than it is to transport electricity from the power source to electrolyzers located near demand centers.

5. Economics of LCI Hydrogen Storage

Pure hydrogen is traditionally stored on a large scale in salt caverns, but this remains a challenge in geographic regions where supporting geology

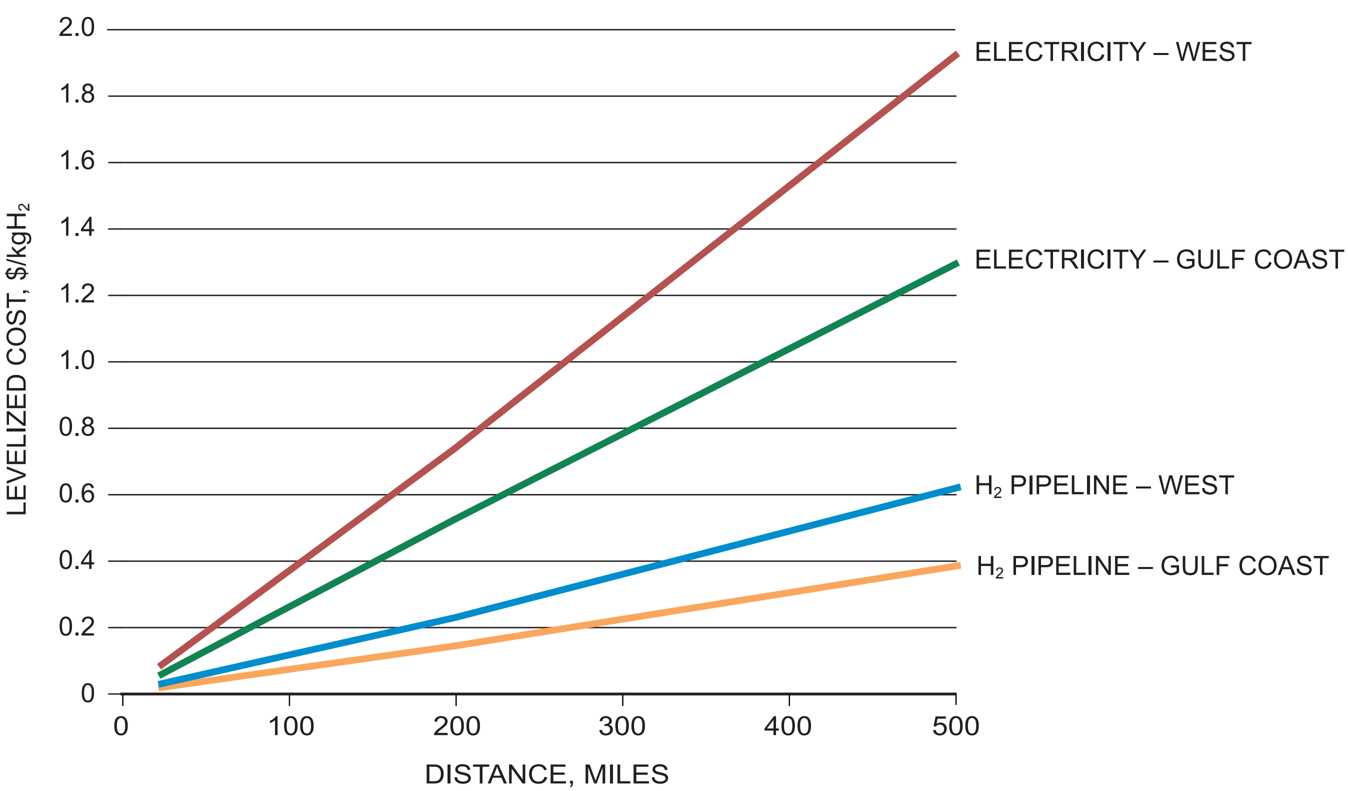


***Figure 3-17.** Levelized Cost of Transmission of Electricity Versus Hydrogen*

does not exist. Alternative storage options include rock caverns and depleted oil and gas reservoirs. However, rock caverns are more expensive to develop than salt caverns, and storage of hydrogen in depleted oil and gas reservoirs is not yet commercially proven at-scale (see Section IV.E.1 of this chapter). Liquid carrier alternatives (such as anhydrous ammonia and LOHCs) can act as relatively low-cost storage alternatives, but incur significant costs associated with conversion to the stored product and reconversion back to hydrogen. LOHCs also lack significant commercial experience, and ammonia carries additional safety considerations that could challenge deployment.

This section considers the cost of large-scale hydrogen storage in its pure form. Three technology pathways are considered: 1) underground storage in salt caverns, 2) liquefied storage in large spheres, and 3) compressed gas pipe farms. Salt caverns and LH_2 storage are currently used in industry, while compressed gas pipe farms, buried just below ground level, have been demonstrated in natural gas service at modest capacities. Pipe farms are considered for nongeologic compressed gas storage as a relatively low-cost option compared to traditional stationary (aboveground) high-pressure tube arrays typically operating at 500+ bar.

Capital and operating costs informing the economics of storage are drawn from a survey of public literature, including the International Journal of Hydrogen Energy, International Energy Agency (IEA) Global Hydrogen Review, DOE Technical Targets For Hydrogen Delivery, and the Hydrogen Delivery Scenario Analysis Model.[108] Capital costs are categorized to reflect costs associated with the actual physical storage and the costs associated with processing the hydrogen into and out of storage (compression, liquefaction, regasification). All the above pathways assume gaseous hydrogen delivered to the point of receipt at the storage facility at an operating pressure of 30 bar.

Cavern storage capital cost includes geological site prep, well drilling, and cushion gas. Pipe farm capital cost is modeled as a string of pipeline segments. A 30% contingency factor is applied to the published pipe farm capital costs considering the lack of real-world references. Liquefied storage capital cost includes liquefaction, sphere storage, and regasification. Boil-off for liquid storage is minimized at 0.03% by leveraging liquefaction facilities for recovery. (See Appendix M: Economics of LCI Hydrogen Transportation, Storage, and Delivery, Table 3-12.)

Salt caverns will likely be the predominant, large-scale hydrogen storage pathway driven by low-cost and high-technological maturity. It is evident from Figure 3-18 that the levelized cost of storage using salt caverns ($0.36/kg H_2 at full utilization)[109] is significantly more cost effective than liquid and compressed gas pipe farm storage ($2.40/kg and $3.23/kg hydrogen, respectively). The levelized cost of storage is primarily driven by asset lifetime and utilization (see Appendix M: Economics of LCI Hydrogen Transportation, Storage, and Delivery, Table 3-12). Low utilization rates increase the cost of storage for all technologies by similar percentages, resulting in particularly high $/kg cost risk for underutilized liquid and pipe farm assets.

Nonetheless, geologic salt cavern storage is not available in all regions as illustrated in Figure 3-19, potentially necessitating the development of other storage technologies.

Despite this limitation on geologic salt cavern storage, within the continental United States, it is still preferable, at least on a purely levelized cost basis, to link regions with underground storage to other parts of the country via high-capacity pipelines in most cases. This is due to the relatively low costs associated with underground storage and pipeline transport. It is an arrangement that can be aspired to with a fully mature hydrogen ecosystem but has practical limitations in the near- to medium-term. Regional networks outside areas with salt cavern storage will need to rely on liquid and/or compressed gas pipe farm storage to meet business needs. Even with adequate geology, the absence of reliable underground storage systems could necessitate liquid and/or compressed gas pipe farm storage systems as well.

108 Argonne National Laboratory, 2014.

109 Utilization rate defined as the ratio of actual throughput (kg/yr) to the maximum design throughput (kg/yr).

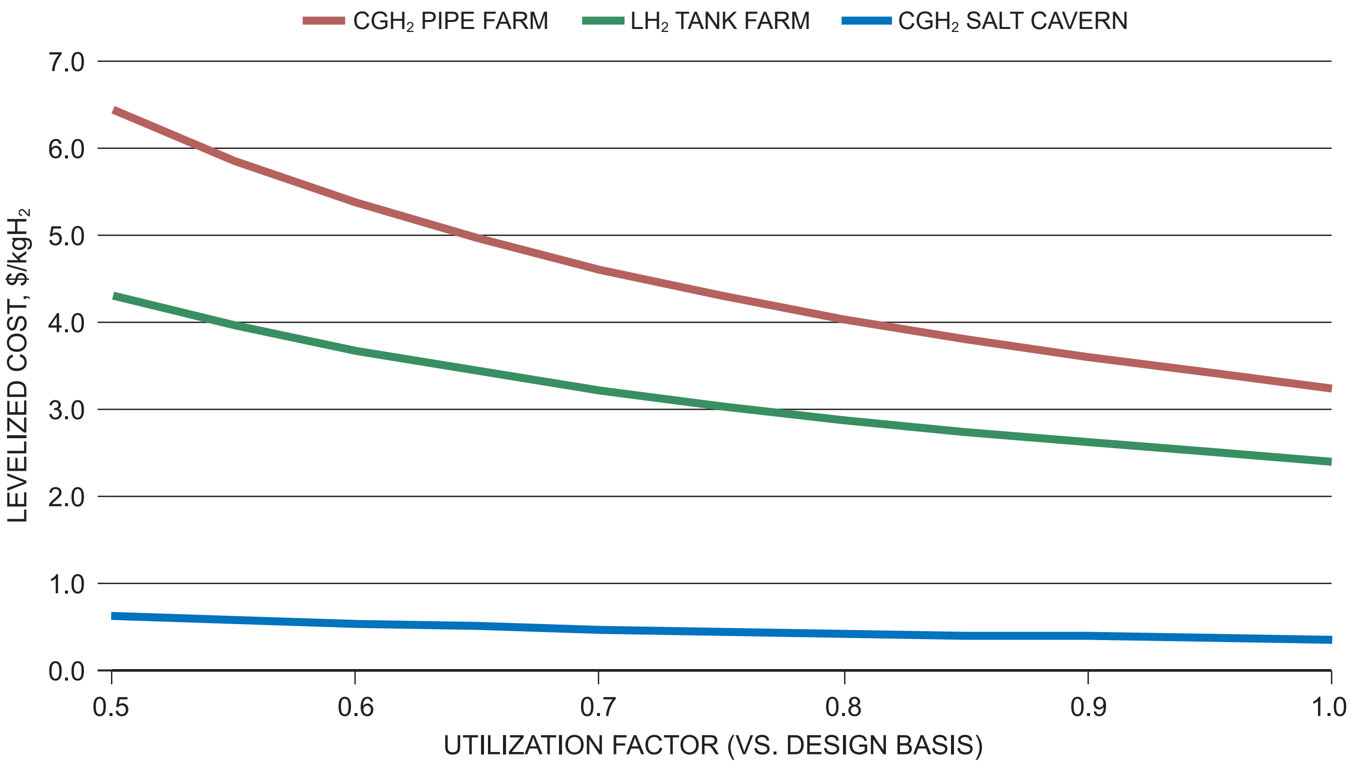
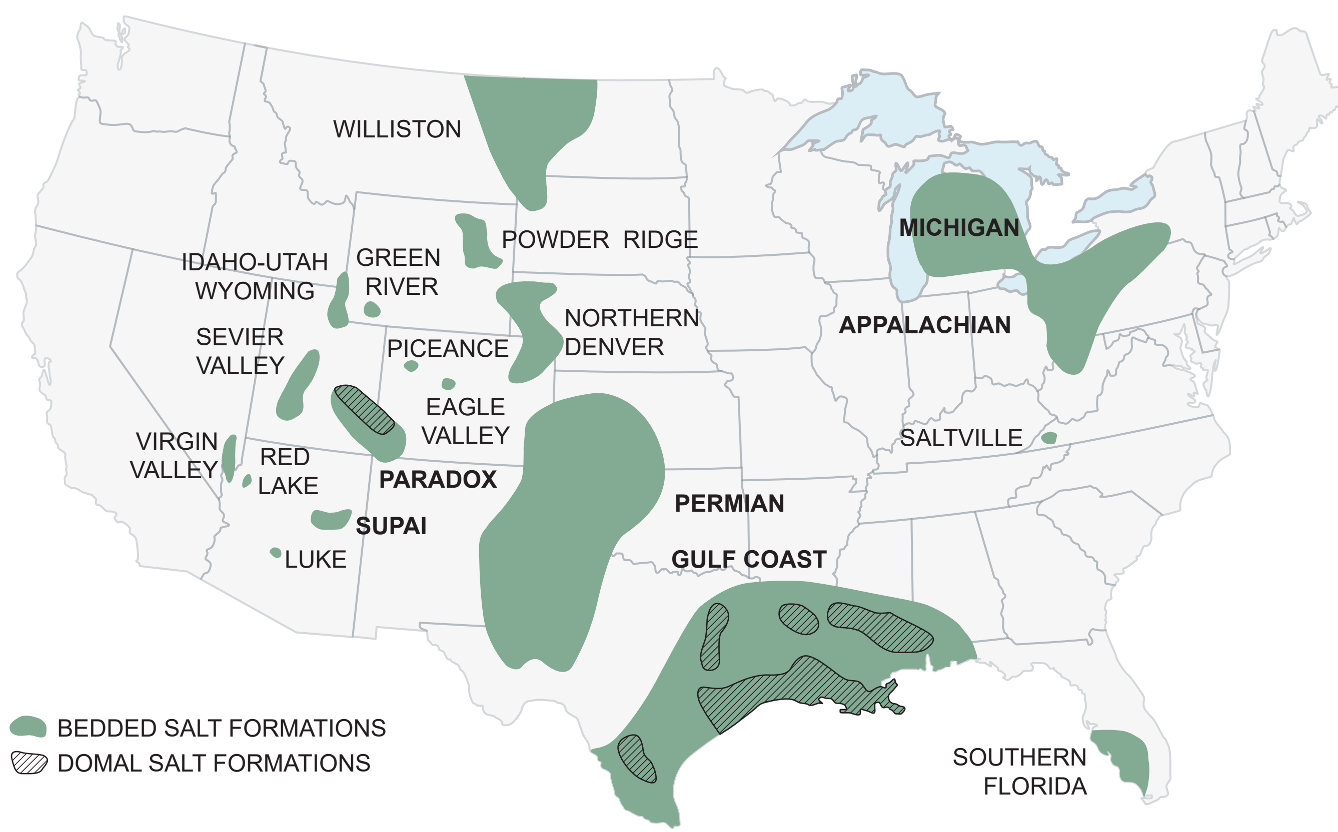


Figure 3-18. *Levelized Cost of Hydrogen Storage in Salt Caverns, Pipelines, and Tanks*



Source: Lin, et al., 2024.

Figure 3-19. *Major U.S. Salt Deposit Formations*

When liquid or compressed gas pipe farm storage is required, the choice between the two depends strongly on the usage (injection and discharge) profile. From the storage system perspective, this can be characterized by the design turnover rate based on the working capacity volume of the storage facility. The base evaluation described above considers a rate of 36 turnovers/year for large-scale liquid and compressed gas pipe farm storage, with the results indicating a preference toward liquid storage. As the design turnover rate increases, however, the preference shifts toward compressed gas pipe farm storage. This shift is depicted in Figure 3-20 and is driven by the hydrogen processing component of the storage cost. At high turnover rates, substantial investment in compression or liquefaction/regasification facilities is required. Since the unit cost of liquefaction/regasification is significantly higher than compression alone, these costs begin to dominate the overall levelized cost of storage.

6. Economics of CO_2 Transportation and Storage Infrastructure

The production of LCI H_2 by SMR or ATR requires supporting CCS infrastructure. This section evaluates the cost drivers for CO_2 transportation and storage infrastructure (see Chapter 2: Production for additional information on carbon capture technologies and associated economics). The economics of carbon utilization is currently beyond the scope of this evaluation. Although the 45Q tax credit provides a definitive range of values for CO_2 utilization, the cost of utilization is highly dependent on the specific process and end-use requirements (e.g., the idiosyncrasies associated with the economics of producing low-carbon cement products from captured CO_2 will be different from the economics of utilizing the same captured CO_2 for producing food and beverage-grade CO_2). Furthermore, the market size of CO_2 utilization is expected to be small relative to the potential for CO_2 storage.[110]

Economics of CO_2 transportation infrastructure: This evaluation uses a national average levelized cost of \$0.15/MT-CO_2-mile for CO_2 transportation based on multiple existing

110 National Petroleum Council. 2019. "Meeting the Dual Challenge: A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage." See Chapter 9. https://dualchallenge.npc.org/files/CCUS-Chap_9-030521.pdf.

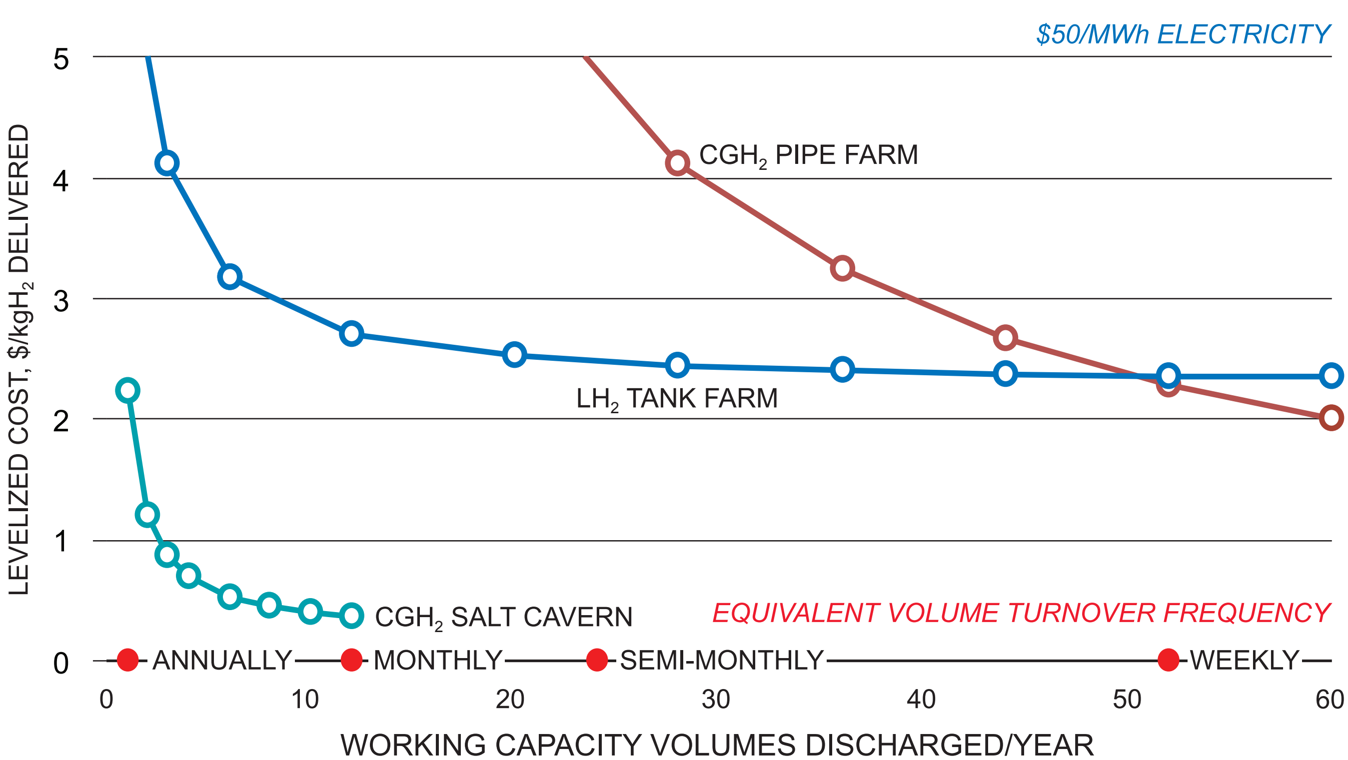


***Figure 3-20.** Levelized Cost of Storage in Delivered Versus Design System Turnover*

literature surveys, including third-party market research data, metrics of recent similarly scaled CO_2 trunkline projects,[111] and informed by the National Petroleum Council's (NPC) *Meeting the Dual Challenge* study.[112] The CO_2 transportation economic evaluation also leveraged the Pipeline and Compression Cost Study,[113] which estimates the regional adjustments for hydrogen pipelines. The regional adjustments from the above study act as a proxy to differentiate the CO_2 transportation costs for the 11 U.S. regions evaluated as part of this study (see Chapter 4: Integrated Supply Chain). The economics of CO_2 transportation include the impact of pipeline capital and operating costs, needed rates of return, and supply and demand circumstances for other CO_2 transportation alternatives (in all circumstances, hydrogen producers will seek to reduce the costs of CO_2 transportation and storage).

While government incentives will shape the deployment of CCS infrastructure specific to the production of LCI H_2, for simplicity the costs assumed here do not reflect the impact of government incentives. It is important to note that incentives from both federal and state governments (the 45Q tax credit or any grant award funding from DOE's IIJA funding opportunities targeting CCS) would be important for a project developer to analyze to determine their project-specific economics.

Economics of CO_2 storage infrastructure: Similar considerations (as detailed above for CO_2 transportation) can be extrapolated for CO_2 storage infrastructure. One would seek to minimize the cost of CO_2 storage and choose a site near the CO_2 capture facility to the extent that it is feasible, safe, and has enough storage capacity to do so. For this evaluation, the CO_2 storage costs were categorized across two cost tiers; one at \$8/MT-CO_2 stored and the other at \$12/MT-CO_2 stored, respectively. The 11 U.S. regions evaluated as part of this study were then assigned to the appropriate cost tiers (see Appendix M: Economics of LCI Hydrogen Transportation, Storage, and Delivery, Table 3-13).

Levelized cost for transportation and storage: The levelized cost for CO_2 transportation and storage for the two different cost tiers is shown in Figures 3-21 and 3-22.

VI. CAPACITY NEEDS ASSESSMENT FOR LCI HYDROGEN INFRASTRUCTURE DEVELOPMENT

A. Introduction

The expansion of LCI H_2 infrastructure capacity will have far-reaching consequences for the growth and development of the hydrogen economy in the United States and for the worldwide energy ecosystem.

To meet the 75 MMTpa[114] of U.S. LCI H_2 demand by 2050 (as evaluated under the Modeling scenarios, see Chapter 4: Integrated Supply Chain), an optimal capacity mix of connecting infrastructure will be needed that is capable of transporting, storing, and delivering varying regional supply and demand needs and to enhance overall system flexibility to support a robust reliable and resilient network. Rapid expansion of LCI H_2 capacity in the United States is necessary to connect strategic supply with demand by 2050.

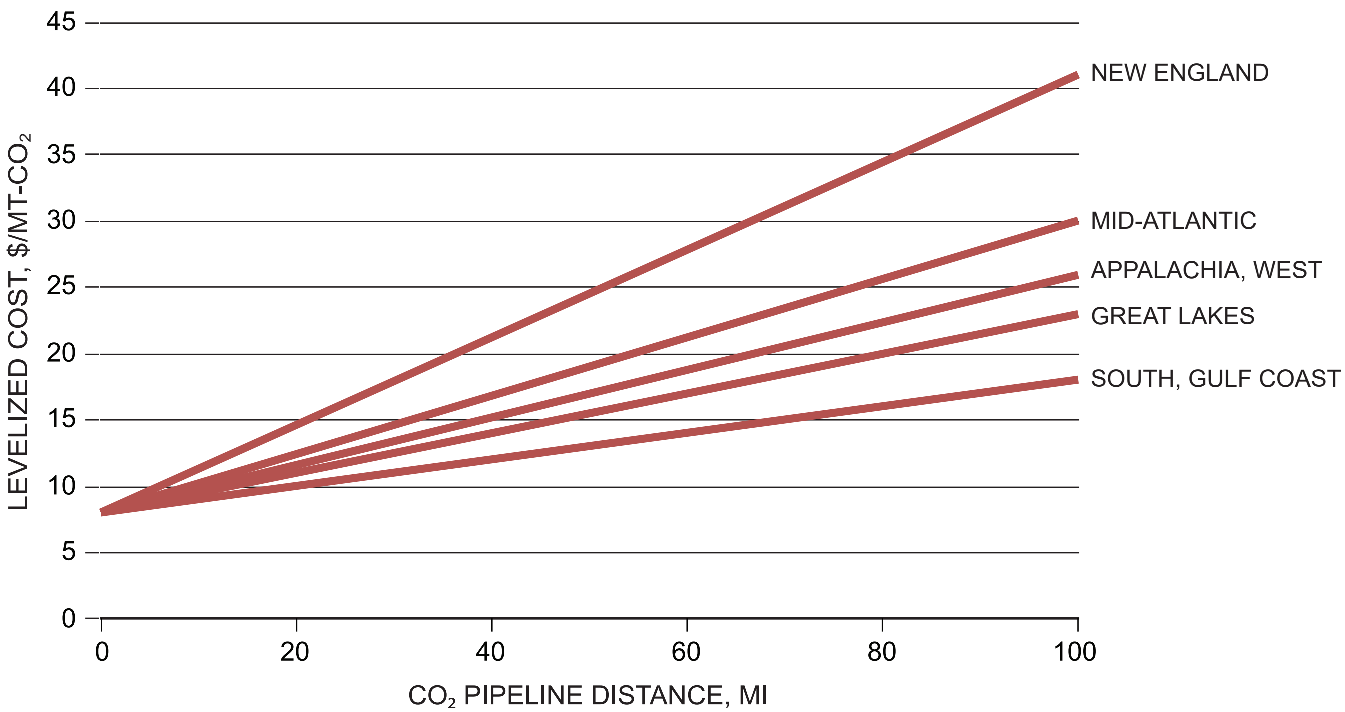
In real-life scenarios, the value proposition (strategic benefits) of specific technologies needed to build infrastructure capacity over a planning horizon must be evaluated across multiple decision variables in addition to comparing the benefits across other alternative technologies beyond LCI H_2.

111 The \$0.15/mile-ton unit basis was triangulated from a collection of industry estimates on CO_2 pipeline transportation, with emphasis placed on DOE's Carbon Management Lift Off Report (https://liftoff.energy.gov/carbon-management/). The midpoint of the DOE estimates (\$/MT range of \$5-25) is \$15/MT. DOE estimates an average project size of roughly 180–300 km (or 111 miles to 186 miles, as referenced in the INGAA 2018 "North American Midstream Infrastructure through 2035" report). Using the conservative end of this range defines the \$0.15/mile-ton unit basis.

112 National Petroleum Council. 2019. "Meeting the Dual Challenge: A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage." https://dualchallenge.npc.org/.

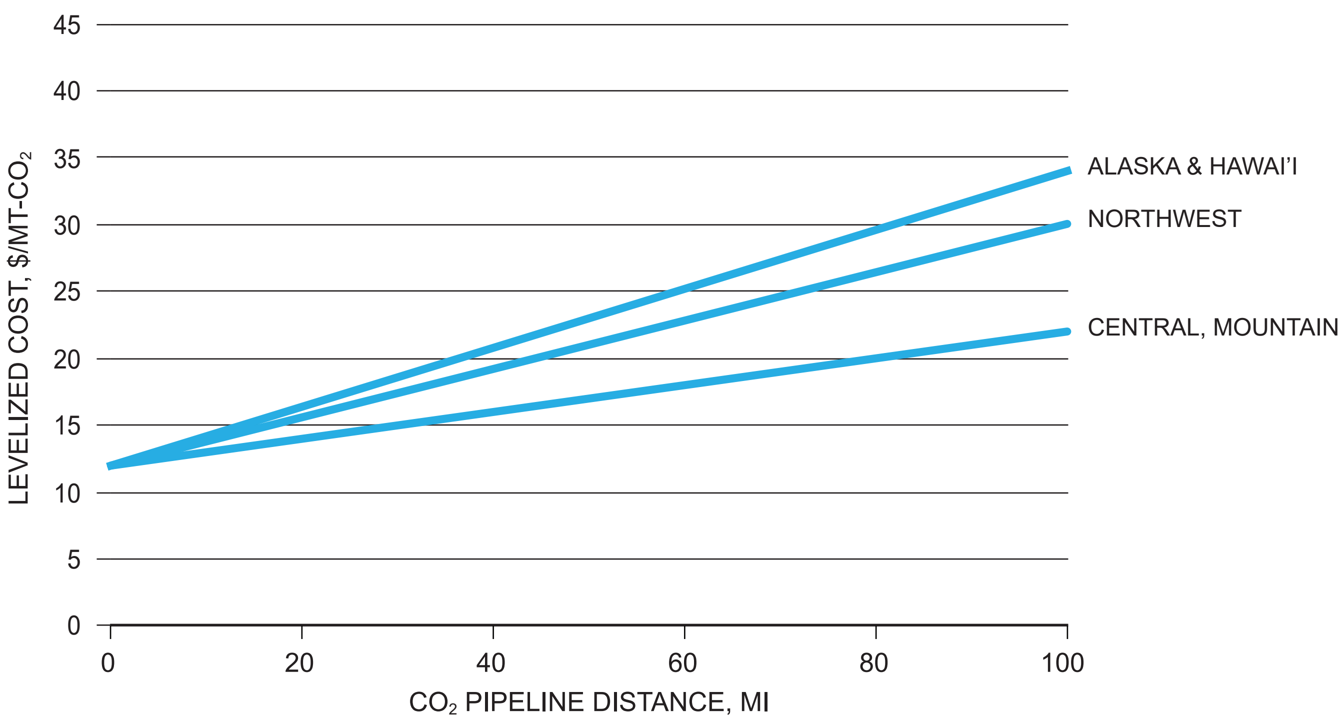
113 Appendix N (https://harnessinghydrogen.npc.org/files/H2-Appendix_N-2024-04-23.pdf) updates the pipeline and compressor construction costs in the 2018 report, "North America Midstream Infrastructure through 2035." Published by Interstate Natural Gas Association of America (INGAA) Foundation.

114 ~75MMTpa of demand projection by 2050 under the Net Zero scenario for the study.



Note: $/MT-$CO_2$ for regions with storage cost of $8/MT-$CO_2$.

Figure 3-21. *Levelized Cost of Transportation and Storage—New England, Mid-Atlantic, Appalachia, West, Great Lakes, South, and Gulf Coast Regions*



Note: $/MT-$CO_2$ for regions with storage cost of $12/MT-$CO_2$.

Figure 3-22. *Levelized Cost of Transportation and Storage—Alaska and Hawai'i, Northwest, Central, and Mountain Regions*

The geographical separation of supply and demand poses additional challenges for deploying LCI H_2 at-scale. Some of these challenges include building infrastructure connecting dispersed supply and demand centers over a vast geographic area (e.g., via pipelines), developing reliable supply (e.g., via salt cavern storage) to reach the desired scale, and reducing the overall infrastructure cost. Transporting molecules from supply centers to various end users of demand could aggravate the inherent cost disparity between LCI H_2 and the incumbent fuels. Hence, assessment of infrastructure capacity needs, locally, regionally, and nationally, to support multiple end users by 2050 necessitates the following key actions.

1. Assessment of Regional Supply and Demand Potential

Assessment of regional LCI H_2 supply-demand potential by 2050 under the NZ2050 scenario would enable the phased development of infrastructure capacity requirements and the choice of infrastructure solution. An analysis for the Gulf Coast, the West, and the Great Lakes regions demonstrates that renewable feedstocks for LCI H_2 production are not always located adjacent to demand centers. As a result, significant infrastructure development will be required to connect supply and demand. According to the Modeling scenarios, the transportation, storage, and distribution of LCI H_2 must increase multifold from existing levels to connect the various demand regionally with the production facilities (see Chapter 4: Integrated Supply Chain), driving the need for infrastructure development across these pivotal regions.

2. Phased Expansion of LCI Hydrogen Infrastructure Capacities

Evaluation of regional infrastructure choice should be optimized based on current and future supply and demand requirements for specific end-user requirements in a phased expansion manner. As part of this study, an analysis was conducted on several LCI H_2 integrated value chain pathways (as part of a regional supply chain optimization architecture) driving the choice of a portfolio of regionally driven infrastructure pathways to connect supply and demand (see Chapter 4: Integrated Supply Chain for additional information).

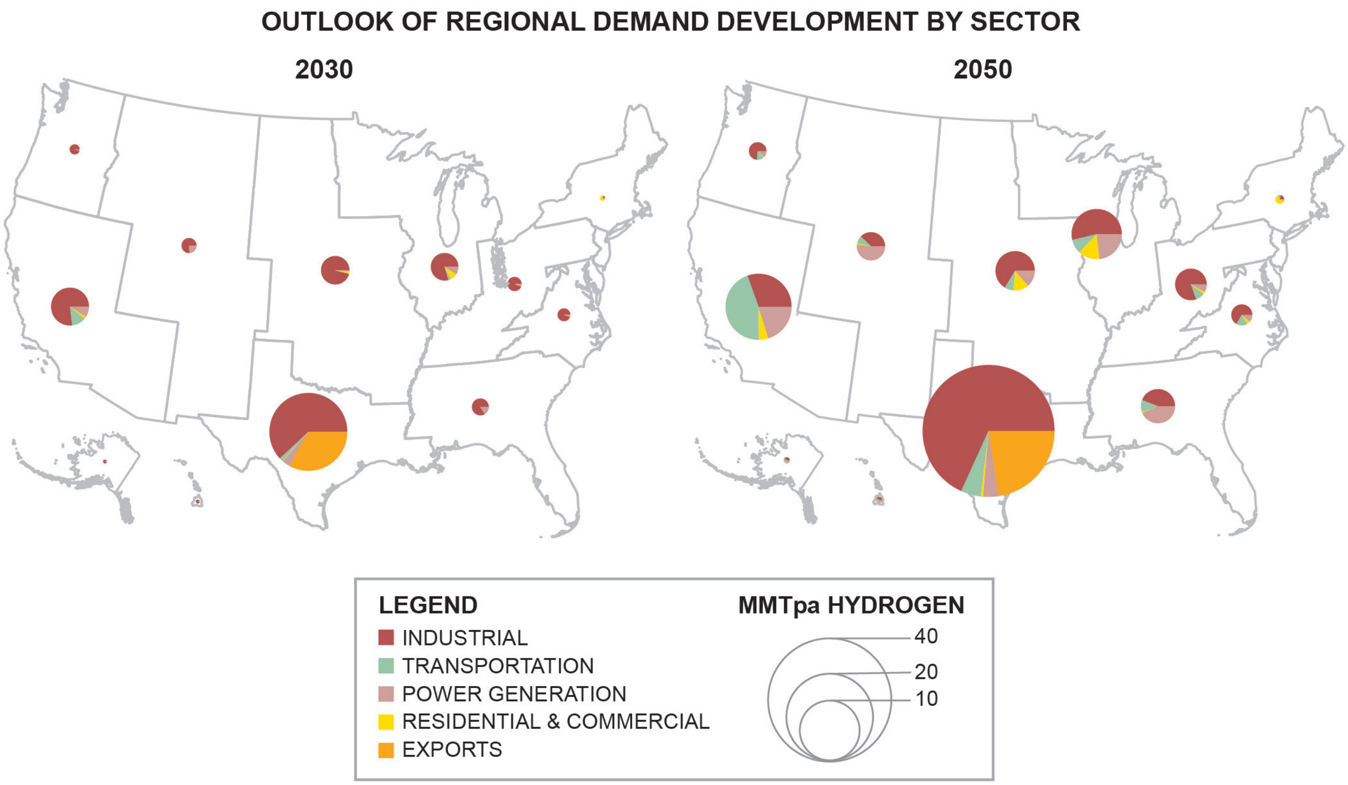
Four key drivers influence infrastructure optimization in the Gulf Coast, West, Central, and Great Lakes regions. These include supply of feedstock for LCI H_2 production, anchor demand across each region, access to infrastructure or ease of development, and policy support. The Gulf Coast and West regions have the potential to be the largest LCI H_2 demand regions, while the Great Lakes and Central regions play an important role in the NZ2050 scenario (see Chapter 5: Demand). These regional demand variances are illustrated in Figure 3-23. Industrial demand for LCI H_2 serves as a demand anchor in most regions and is a crucial enabler of infrastructure construction and expansion.

Based on the Modeling results as illustrated in Figure 3-23, regional variability in LCI H_2 supply by technology type plays a significant role in driving the need for customized infrastructure solutions, especially for renewable electrolytic hydrogen production by region (see Chapter 2: Production). Natural gas reformed LCI H_2 is expected to be near the demand centers, whereas location-specific, high-quality renewables driving LCI H_2 production could make it necessary to develop long-distance LCI H_2 transportation and large-scale storage infrastructure.

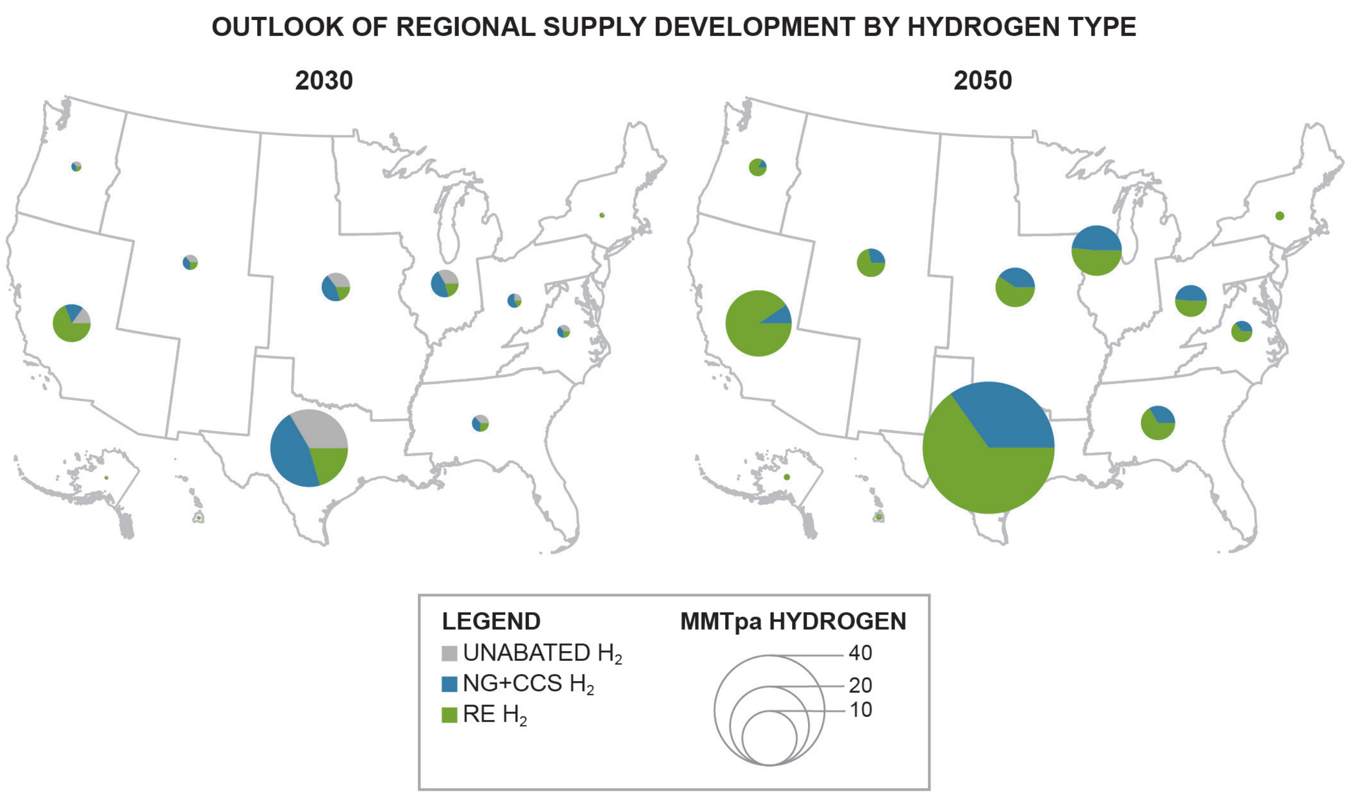
Regional/local clean energy policies (such as those in California) could see a rapid increase in the adoption of LCI H_2 produced from renewables across transportation and power generation sectors, necessitating customized infrastructure capacity buildout to meet the region's specific supply and demand needs.

The need for the development of long-distance connecting infrastructure to address the challenges associated with geographical separation of supply, storage, and demand centers to support a renewable LCI H_2 value chain can be illustrated as shown in Figure 3-24.

Under the NZ2050 scenario, California, with its suite of clean energy policies aimed at meeting state decarbonization targets by the middle of this century, could generate considerable demand for LCI H_2 in the clean transportation, power generation, and industrial end-use sectors by 2050. California's established zero-emissions vehicle (ZEV) policies, such as the



Note: Existing and future anchor demand will impact regional sectoral adoption.



Note: Advantaged regions will develop the early markets for LCI hydrogen.

Figure 3-23. *Regional LCI Hydrogen Demand and Supply Outlook in 2030 and 2050 Under the Net Zero by 2050 Scenario*

Low Carbon Fuel Standard,[115] Advanced Clean Transit (ACT),[116] and Innovative Clean Transit (ICT),[117] provide significant regional competitiveness and policy advantages for the development of necessary infrastructure to meet future LCI H_2 demand to support the FCEV transportation market, including light-, medium-, and heavy-duty trucking and bus fleets. California's Senate Bill (SB)100 requires retail electricity to be sourced from renewable and zero-carbon resources by 2045, enabling LCI H_2 demand to support firm, dispatchable power needs that may not be possible with intermittent solar, wind, and battery storage.[118]

115 California Air Resources Board. 2024. "Low Carbon Fuel Standard." https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard.

116 California Air Resources Board. 2024. "Advanced Clean Fleets." https://ww2.arb.ca.gov/our-work/programs/advanced-clean-fleets.

117 California Air Resources Board. 2024. "Innovative Clean Transit." https://ww2.arb.ca.gov/our-work/programs/innovative-clean-transit.

118 Environmental Defense Fund. 2021. "California Needs Clean, Firm Power, and So Does the Rest of the World." https://www.edf.org/sites/default/files/documents/SB100%20clean%20firm%20power%20report%20plus%20SI.pdf.

Given California's limited access to large-scale salt cavern storage resources, the other western states, such as Arizona, that are endowed with salt cavern resource potential could provide synergistic regional resource benefits to enable the region's development of LCI H_2 infrastructure. The abundance of solar/wind resources in eastern and central California, combined with the potential underground geologic salt cavern resource in western Arizona, could necessitate the development of a long-distance interstate hydrogen pipeline network. Those factors could also require the creation of further infrastructure synergy to support last mile delivery infrastructure (e.g., CGH_2 or LH_2 trucks) needed to serve the various end users in the western region (see Chapter 4: Integrated Supply Chain for key insights about the regional infrastructure optimization across the Gulf Coast, the western United States, and the Great Lakes, highlighting the factors driving the infrastructure cost variability and influencing the delivered cost of LCI H_2).

The development of LCI H_2 infrastructure will face a variety of unique challenges, as well as distinct market barriers that must be overcome

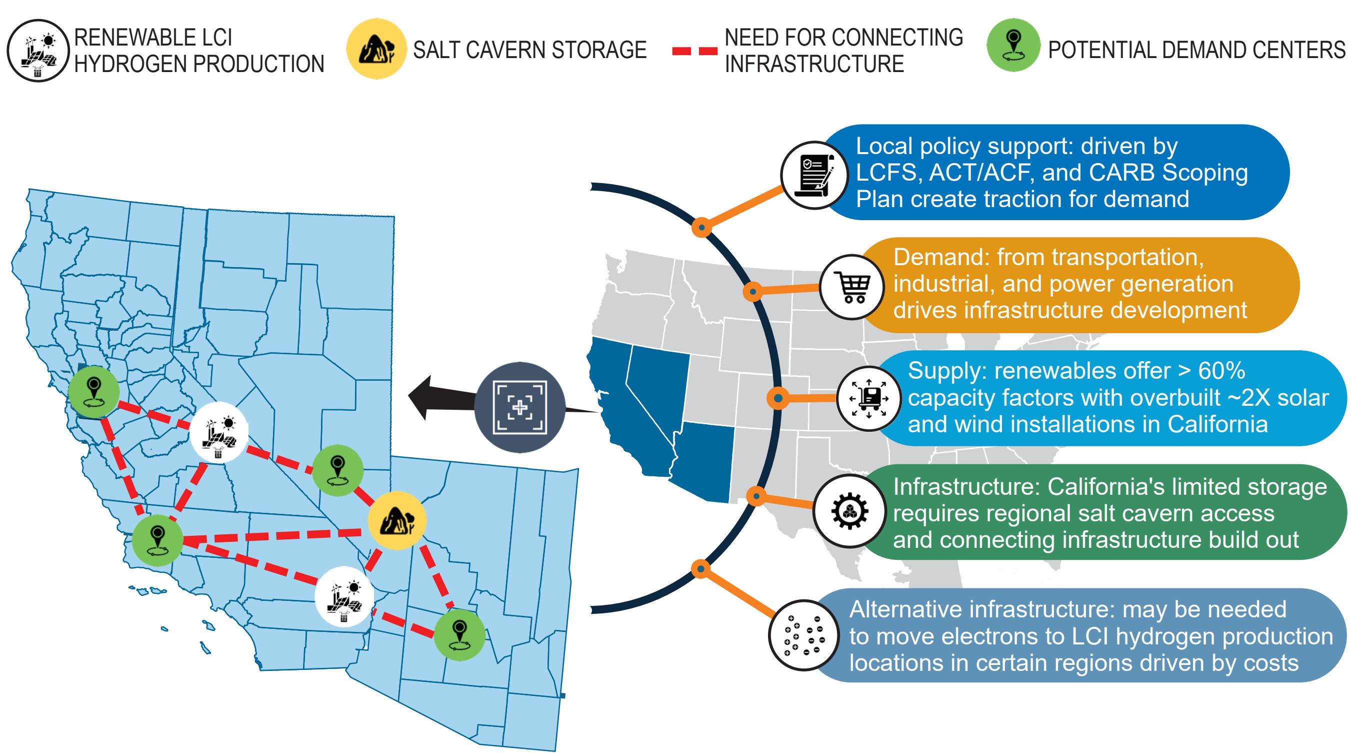


Figure 3-24. *Western Region Drivers Connecting Supply and Demand*

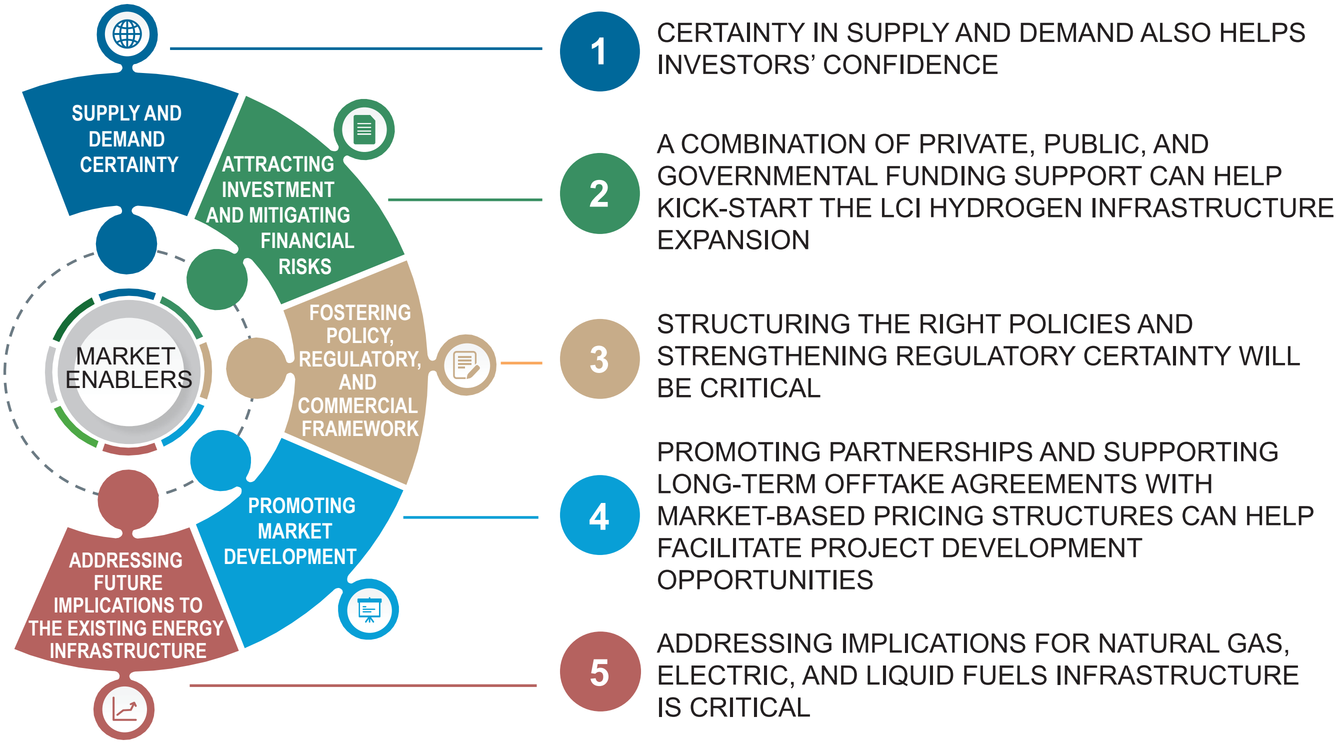


Figure 3-25. *Market Development Enablers for LCI Hydrogen Infrastructure Expansion*

to enable the initial Activation phase and subsequent Expansion and At-Scale phases. Strategic planning by infrastructure developers across all three phases and sequencing of hydrogen transport, storage, and delivery infrastructure rollout will have significant implications not just for the growth and development of the hydrogen economy in the United States, but also for the entire energy ecosystem.

B. Market Development Enablers for LCI Infrastructure Expansion

Acting on market-based, commercially driven infrastructure development enablers, as shown in Figure 3-25, can help foster the development of an efficient, flexible, and resilient LCI H_2 market.

Connecting localized and regional hydrogen supply with geographically dispersed end-use demand determines the connecting infrastructure system capacity, and the overall benefits of transportation, storage, and delivery infrastructure development. The development of the LCI H_2 infrastructure cannot be considered in isolation due to the interconnectedness of the wider energy ecosystem in the United States, including liquid fuels, natural gas, and the electricity grid.

The development of market-based, commercially driven infrastructure enablers based on locational requirements and interactions with the wider energy system can help facilitate the development of an efficient, flexible, and resilient LCI H_2 market. Potential strategic enablers to meet the above objectives involve:

1. Creating a Market Supporting Supply and Demand Certainty

Investments in LCI H_2 infrastructure require a level of certainty around the supply and demand of hydrogen over the planning horizon so that enough investment capital is flowing to ensure the infrastructure meets the future supply and demand requirements. Certainty in supply and demand also helps investors' confidence to support the nascent hydrogen economy. Government backed incentive frameworks can help build certainty about demand and supply in the United States. The recently passed IIJA and IRA incentive programs in the United States can spur significant demand for hydrogen in the coming years.

There is global momentum to set production targets and kick-start hydrogen demand. As of 2022, the Hydrogen Council estimated that 40 countries have set national hydrogen strategies globally to leverage hydrogen's decarbonization potential, ensure energy security, and support sustainable economic growth.[119] The European Commission as part of its REPowerEU plan, has set ambitious goals to produce 10 MMT of hydrogen in the European Union and import an additional 10 MMT of renewable hydrogen by 2030.[120] See Chapter 6: Policy highlighting various hydrogen activities across several countries summarizing their hydrogen strategies, deployment targets, demand, and supply policies.

Adopting target measures as discussed previously and supporting market development incentives to ensure long-term supply and demand certainty, can help boost investor confidence and enable the development and expansion of the hydrogen infrastructure across the entire value chain.

2. Attracting Investment and Mitigating Financial Risks

Future revenue uncertainty for original equipment manufacturers (OEMs) and hydrogen project developers can be a significant barrier for LCI H_2 infrastructure development and for garnering appetite for investment in the LCI H_2 economy. This can potentially lead to prolonged, or prevented, Final Investment Decisions (FID) for the scheduled projects. With significant upfront capital required to scale the hydrogen infrastructure in the United States during the Activation and Expansion phases, a lack of supportive investment and incentive mechanisms could negatively impact investor confidence in the development of the hydrogen infrastructure projects.

FID delays, cash flow uncertainties, and the perceived inability of the developers to recover investment costs can lead to project delays, financial defaults, and stranded assets. A combination of private, public, and governmental funding support can help kick-start the LCI H_2 infrastructure projects in the United States and mitigate the risk-return valuations of project investments. Federal, regional, state, and municipal governments can mobilize green bond funding schemes, loans, grants, tax credits, etc., via bilateral or multilateral arrangements with financial institutions to help deliver the large capital investments needed. Institutional investors, including sovereign wealth funds, pension funds, insurance companies, and asset management companies, can also play a strategic investment partnership role to scale up LCI H_2 infrastructure development in the United States.

3. Providing the Right Policy, Regulatory, and Commercial Framework

Structuring the right policies and strengthening regulatory certainty for LCI H_2 infrastructure development will be critical to rapid scaling and expansion to meet the future demand for hydrogen in the United States. Fast tracking project funding to accelerate development and streamlining the NEPA and project permitting regulations and approval timelines, can help projects meet FID and the infrastructure capacity expansion targets in a timely manner to garner long-term feedstock and supply contracts across various end-use sectors of demand. Assessing the existing hydrogen market development and commercial enabling frameworks in the United States to identify key gaps and barriers for the development of LCI H_2 transportation, storage, and delivery infrastructure will be essential. Removing commercial gaps and uncertainties for companies to own, operate, and maintain hydrogen infrastructure will be vital in ensuring the right engagement of OEMs, infrastructure operators, delivery companies, and users of LCI H_2. Successfully implementing the right commercial arrangements across the supply chain to scale and operate the future LCI H_2 infrastructure network will further support all stakeholders.

4. Promoting Market Development to Advance Infrastructure Expansion

Promoting market partnership consortiums with key stakeholders and supporting long-term

119 Hydrogen Council. 2022. "Hydrogen Insights 2022: An Updated Perspective on Hydrogen Market Development and Actions Required to Unlock Hydrogen at Scale." https://hydrogencouncil.com/wp-content/uploads/2022/09/Hydrogen-Insights-2022-2.pdf.

120 European Commission. 2022. "Hydrogen." https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en#:~:text=Hydrogen%20accelerator.

offtake agreements with market-based pricing and incentive structures can help facilitate project development opportunities. Promoting and investing in Pre-Front End Engineering and Design (Pre-FEED) and FEED studies enables commercially viable projects to transition from proposals closer to deployment. Harmonizing hydrogen production and carbon intensity standards at local, state, regional, and national levels can help fast-track infrastructure development and incentivize interstate LCI H_2 import/export markets. Encouraging further research and development of all LCI H_2 transportation, storage, and delivery technologies to create a cost-effective and sustainable infrastructure solution for all stakeholders will be critical in allowing emerging technologies to become mainstream market development solutions over the long term.

5. Addressing Future Implications to the Existing Energy Infrastructure

LCI H_2's role as a new low-carbon energy carrier in the United States will have implications for the existing energy infrastructure that supports liquid fuels, natural gas, and electric grids.

Implications for natural gas infrastructure: The development of LCI H_2 transportation, storage, and delivery infrastructure will have local and regional implications for the existing natural gas system. If the existing natural gas infrastructure is repurposed, it will be important to ensure that the natural gas system's operational functionality, safety, reliability, and resiliency are maintained for as long as consumers connected to the system are reliant on it for their energy needs, along with the commercial considerations for repurposing existing infrastructure.

Implications for electric grid infrastructure: The integration of the electric grid with the LCI H_2 infrastructure can have profound synergistic benefits as part of the growing interdependence of multiple energy subsector infrastructures to support the decarbonization needs. (See Section XI.F of this chapter.)

Implications for liquid fuels' infrastructure: LCI H_2 can play an important role in supporting the development of low-carbon fuels (sustainable aviation fuels, bioderived kerosene and diesel, methanol, and hydrogen carrier fuels) as transportation fuels by utilizing carbon neutral LCI H_2 and, if required, synthesizing it with CO from DAC or biogenic sources. Due to the similar operational characteristics of low carbon intensity liquid fuels (in relation to traditional liquid fuels), leveraging the existing transportation, storage, and delivery infrastructure has the potential to help reduce incremental investment costs and support the transition to a cleaner energy ecosystem supporting multiple end-use demand sectors, including heavy-duty transportation, rail, shipping, and aviation.

VII. DEVELOPMENT PATHWAYS FOR LCI HYDROGEN INFRASTRUCTURE

A. Introduction

LCI H_2 infrastructure development is expected to progress via three pathways as illustrated in Figure 3-26: 1) blending of LCI H_2 into existing natural gas infrastructure; 2) conversion of existing energy infrastructure into dedicated hydrogen service; and 3) construction of new LCI H_2 infrastructure.

As compared to building entirely new LCI H_2 infrastructure, blending LCI H_2 into existing natural gas infrastructure or repurposing existing infrastructure to dedicated LCI H_2 service could result in cost savings and a shorter timeline for LCI H_2 deployment. Technical feasibility, end-use demand, and potential environmental/community impacts all must be evaluated prior to blending or repurposing. Collaboration between industry, DOE, PHMSA, and other research institutions is needed to develop best practices, technical standards, and guidelines for blending and repurposing. It should be reinforced that no volume of hydrogen should be blended into existing infrastructure without a comprehensive assessment to verify the ability to transport hydrogen safely and reliably. A NREL study on hydrogen blending notes a wide range of acceptability of blend percentages (between 5% and 20%).[121] A different NREL hydrogen blending study emphasizes case-by-case assessment of blending based

121 Melaina, M.W., Antonia, O., and Penev, M. 2013. "Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues." https://www.nrel.gov/docs/fy13osti/51995.pdf.

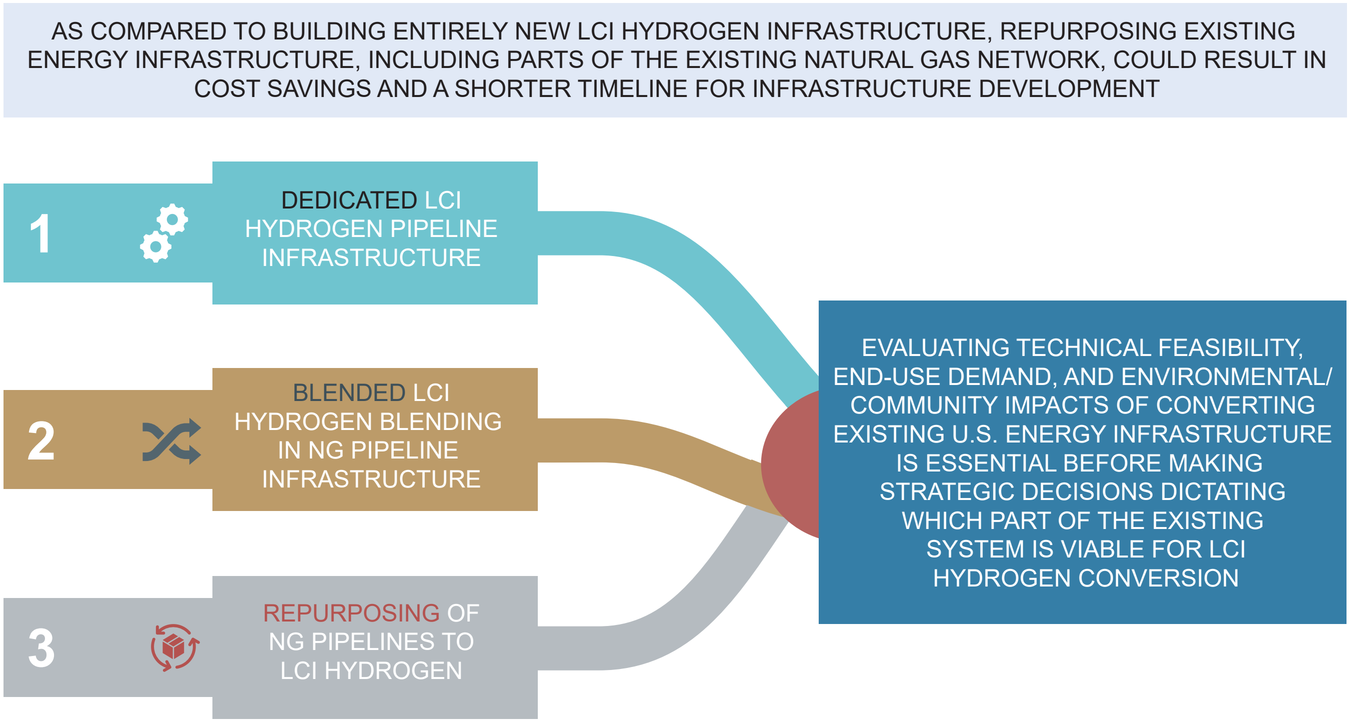


Figure 3-26. *Role of Existing Natural Gas and New LCI Hydrogen Infrastructure to Address Long-Term Energy Infrastructure Viability*

on pipeline characteristics[122] and a University of California-Riverside hydrogen blending impacts study indicates concerns of hydrogen's effects on the existing natural gas infrastructure as the system-wide blending levels approach 5%. The study emphasizes that to minimize the impact on materials, components, facilities, and equipment, hydrogen blending should be done in stages and with careful planning.[123] The deployment of LCI H_2 at-scale will also require the development of new infrastructure where existing infrastructure doesn't exist or cannot be repurposed.

B. Role of Existing Natural Gas Infrastructure to Support LCI Hydrogen

According to the EIA, the United States' natural gas pipeline infrastructure is a highly mature and integrated network that transports natural gas across the continent (as shown in Figure 3-27). As of 2021, the United States had approximately 301,254 miles of natural gas transmission pipelines[124] and 2,300,793 miles of natural gas distribution mains[125] to support delivery to approximately 77.7 million consumers.[126] A variety of entities manage the natural gas infrastructure network in the United States, including interstate and intrastate pipeline and storage operators, local distribution companies, and local city and municipal agencies. The key infrastructure elements of the natural gas system include:

122 Topolski, K., Reznicek, E., Erdener, B., San Marchi, C., Ronevich, J., Fring, L., Simmons, K., et al. 2022. "Hydrogen Blending into Natural Gas Pipeline Infrastructure: Review of the State of Technology." https://www.nrel.gov/docs/fy23osti/81704.pdf.

123 Raju, Arun S.K., Alfredo Martinez-Morales. 2022. "Hydrogen Blending Impacts Study, Final Report." Prepared for the California Public Utilities Commission. https://docs.cpuc.ca.gov/PublishedDocs/Efile/G000/M493/K760/493760600.PDF.

124 DOT PHMSA. 2023. "Gas Pipeline Leak Detection and Repair." May 4, 2023, p.36. https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/2023-05/Gas%20Pipeline%20Leak%20Detection%20and%20Repair%20NPRM%20-%20May%202023.pdf.

125 DOT PHMSA. 2023. https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/2023-05/Gas%20Pipeline%20Leak%20Detection%20and%20Repair%20NPRM%20-%20May%202023.pdf.

126 EIA. 2024. "Natural Gas Explained." https://www.eia.gov/energyexplained/natural-gas/natural-gas-pipelines.php#:~:text=The%20U.S.%20natural%20gas%20pipeline,and%20storage%20facilities%20with%20consumers.

Natural gas transmission pipelines: Transmission pipelines are large diameter (typically 24-42 inches), high-pressure (typically up to ~1,440 psig.) pipelines used for long-distance transport from production areas to consumption areas. The transmission network also includes supporting infrastructure, such as compressor stations and measurement and control systems.

Natural gas storage facilities: Natural gas storage facilities, including underground salt caverns, saline aquifers, and depleted oil and gas reservoirs, are used to store natural gas and support overall system reliability and resiliency.

Natural gas distribution infrastructure: Natural gas distribution infrastructure includes smaller diameter pipelines (typically 6 to 20 inches), piping, equipment and facilities used to deliver natural gas to end users (homes and businesses). This includes meters to determine the amount of energy delivered, along with regulators and other equipment to control the flow and pressure of the gas.

There are two potential pathways to leverage the existing natural gas system to transport LCI H_2 at-scale:

- **LCI hydrogen blending:** LCI H_2 produced through various production pathways can be injected into the natural gas network through blending stations, which include metering and controls to ensure that the correct ratio of LCI H_2 to natural gas is maintained. The blended gas is then transported through the natural gas network to end users. Given the scale of the existing natural gas infrastructure in the United States, blending could potentially reduce CO_2 emissions at a lower capital cost versus other alternatives.
- **Full conversion to LCI H_2:** Full conversion of existing natural gas infrastructure to hydrogen service, while uncommon[127] in the past, may emerge as an effective strategy for increasing hydrogen transport capability.[128]

127 One notable exception is Air Liquide, which, in the 1990s, successfully demonstrated the conversion of two crude oil pipelines in Texas to transport hydrogen.

128 Congressional Research Service. 2021. "Pipeline Transportation of Hydrogen: Regulation, Research, and Policy." https://crsreports.congress.gov/product/pdf/R/R46700.

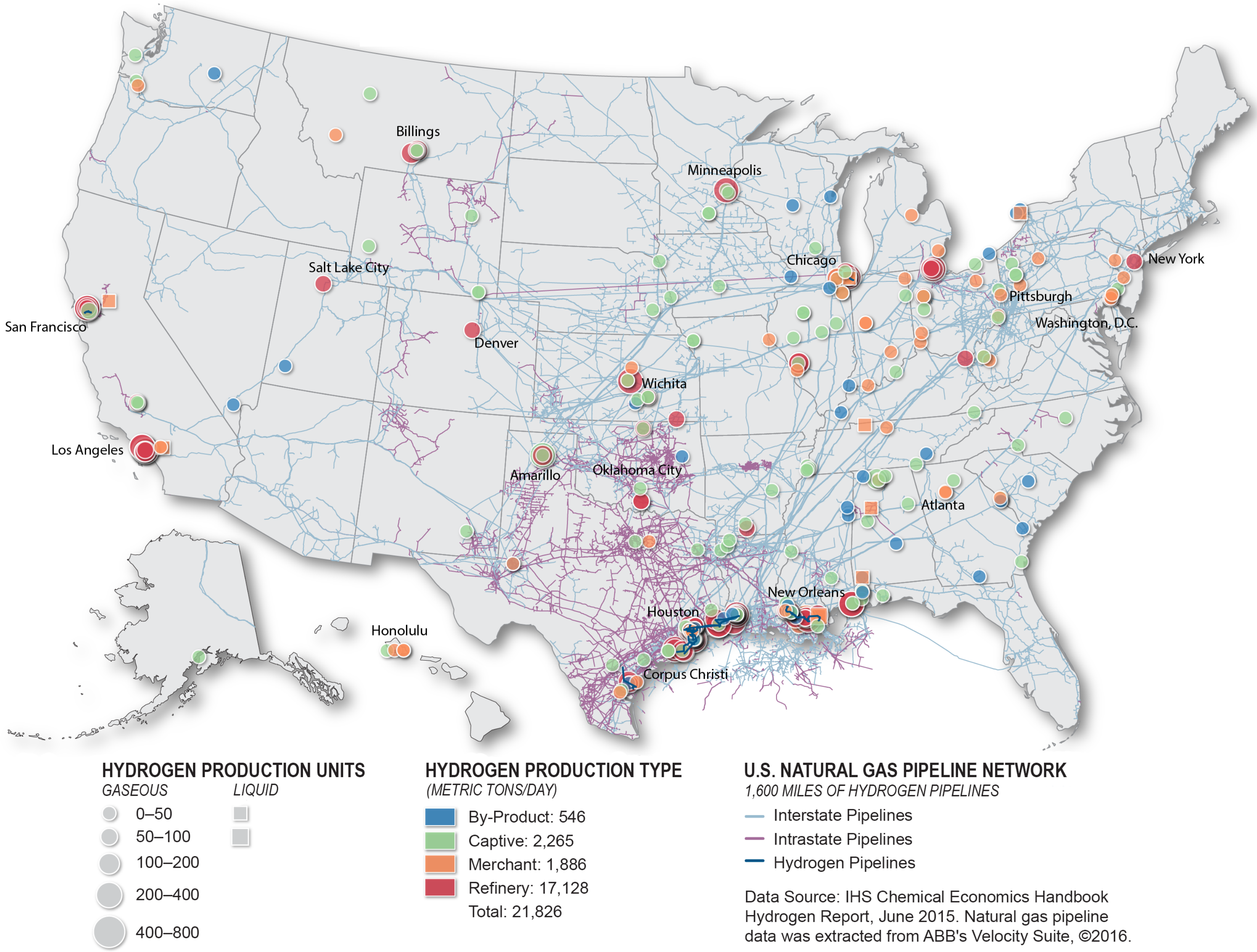
The following sections describe the technical impacts of blending and full conversion, and conclude with a summary of current research, development, and demonstration activities.

1. Technical Impacts of LCI Hydrogen Blending

The blending of hydrogen with natural gas can have several technical impacts on the natural gas transmission and distribution systems:

- **Mechanical integrity:** Hydrogen reduces the fracture toughness of steel and increases fatigue crack growth rates. While typically not a concern in low-pressure distribution pipelines, the impact of hydrogen on high-pressure transmission pipelines must be evaluated. The work being conducted under the DOE HyBlend[129] program, as well as other demonstration projects, will help to define the factors that impact fatigue and fracture resistance. Knowing the impact of increased fatigue crack growth rates and reduced fracture resistance will enable the design of appropriate integrity management programs for hydrogen blends. Where applicable, these integrity programs will likely include a combination of materials testing, pressure cycle management, in-line inspection for cracks, hydrostatic testing, and appropriately conservative repair criteria. In some cases, where existing pipe is not suitable for hydrogen blending, it may be possible to retrofit the pipe using reinforced thermoplastic pipe (RTP). RTP pipe can be pulled through existing steel pipe, offering cost advantages over replacement. However, existing RTP pipe designs are limited to ~8 inches diameter, which will limit the application of this technology.
- **Energy density:** The lower volumetric energy density of hydrogen results in reduced energy transmission at fixed compression capacity. Maintaining equivalent energy transmission requires an increase in volumetric flow rate and compression capacity. The associated

129 DOE. 2022. "HyBlend Design and Operation of Metallic Pipelines for Service in Hydrogen and Blands." DOE Annual Merit Review and Peer Evaluation Meeting. https://www.hydrogen.energy.gov/pdfs/review22/in035_san_marchi_2022_o.pdf.



Source: DOE (NREL), 2023.

Figure 3-27. Existing Natural Gas and Hydrogen Infrastructure in the United States impact of increased velocity and/or pressure must be evaluated.[130]

- **Potential for leakage:** Leak detection technologies and preventive maintenance practices will need to be adapted to address the unique characteristics of hydrogen. Sealing materials in pipelines, compressors, valves, and other equipment will need to be evaluated for suitability in hydrogen service.
- **Compressor stations:** Hydrogen is much less dense than methane and has a higher heat capacity ratio. This results in increased compression work and temperature rise when considering compression at constant pressure rise and inlet temperature. Additional compression capacity may be required to maintain the desired rate of energy transmission. Compressor stations may also become power limited by the compressor motor or turbine.[131]
- **Pressure regulation and metering systems:** LCI H_2 blending in a natural gas system can impact the sizing and operation of pressure regulation devices, which are used to maintain the pressure of the gas in the pipeline within certain limits. According to NREL, there is limited information to evaluate the effect of increasing hydrogen blending on pressure regulator performance.[132] Commonly used flowmeters for natural gas service include orifice meters, turbine meters, and ultrasonic flowmeters. The data processing algorithms used to compensate flowmeters can be adjusted based on hydrogen content. However, online analyzers may also be needed if composition is expected to fluctuate.
- **Underground storage:** The lower volumetric energy density of hydrogen will reduce the capacity of existing storage facilities unless the storage pressure can be increased. Before introducing hydrogen into any subterranean storage facility, the sealing ability of the geological structure should be evaluated. The effect of hydrogen on material properties, and the increased propensity for leakage applies to storage facilities as well, including materials used for well completion. Finally, hydrogen conversion and loss due to subsurface microbial activity is plausible in all subsurface storage but is most likely in depleted oil and gas reservoirs.[133]
- **Distribution impacts:** Because distribution systems operate at lower pressures than transmission systems and are often constructed largely with polyethylene pipe, it is believed there will be fewer challenges involved with blending or repurposing. However, it will be critical to perform a complete assessment of each distribution system's integrity and safety prior to introducing LCI H_2 into the system. The impact of LCI H_2 on the mechanical, physical, and chemical properties, durability of plastic pipes, and the resin formulations used to manufacture the pipes, needs to be studied. LCI H_2 can impact the density and degree of crystallinity of polyethylene pipes.[134] The impact of LCI H_2 on the physical properties of higher-density polyethylene can be different from lower-density polyethylene. Metallic pipe materials (steel and cast-iron pipe, mechanical couplings, etc.) will also need to be evaluated. Finally, the impact of LCI H_2 on nonpipe components in the distribution network (valves, pressure regulators, compressors, metering devices, etc.) should also be well understood.

Leakage of blended gas in distribution networks is also an area of concern for both safety and environmental reasons. Effective procedures for monitoring, identification, and repair of leaks in distribution systems will be needed to ensure safe operation and minimize losses.[135]

2. Technical Impacts of Full Conversion to a Dedicated LCI Hydrogen System

The impacts of converting a system to 100% hydrogen are largely the same as those of blending

130 American Society of Mechanical Engineers. 2021. "Power and Compression Analysis of Power-to-Gas Implementations in Natural Gas Pipelines with up to 100% Hydrogen." September 16, 2021. https://asmedigitalcollection.asme.org/GT/proceedings/GT2021/85017/V008T20A011/1120194.

131 Topolski, K., Reznicek, E., Erdener, B., San Marchi, C., Ronevich, J., Fring, L., Simmons, K., Guerra Fernandez, O., Hodge, B-M., and Chung, M. 2022. "Hydrogen Blending into Natural Gas Pipeline Infrastructure: Review of the State of Technology." National Renewable Energy Agency. October 2022, p. 28. https://www.nrel.gov/docs/fy23osti/81704.pdf.

132 Topolski et al., October 2022.

133 Topolski et al., October 2022.

134 Topolski et al., October 2022.

135 Raju et al., 2022.

(including the end user), only to a greater degree. However, notable areas of difference include the use of odorants to detect leaks that could pose a safety risk, and the use of leak detection technologies for environmental monitoring.

Odorants to detect pure hydrogen leaks that could pose a safety hazard need further evaluation. The Hy4Heat project performed in the United Kingdom evaluated using odorant with 78% 2methyl-propanethiol and 22% dimethyl sulfide hydrogen. This odorant did not show any evidence of damage to distribution pipes and appliances. However, if LCI H_2 with this odorant is to be used in fuel cells, additional purification steps are needed.[136]

Leak detection technologies for monitoring methane emissions can be divided into gas sampling technologies (e.g., flame ionization detectors) and optical methods (e.g., tunable diode lasers, LiDAR, optical gas imaging). Both technology types can detect methane emissions from blended gas systems. However, neither technology type in its current form is effective for detecting pure hydrogen emissions.[137]

3. Existing Regulations, Codes, Standards, and Guidelines

PHMSA plays a key role in ensuring the safety of hydrogen transport by pipeline in the United States. That administration has established requirements for materials, design, construction, operation, inspection, and maintenance of hydrogen pipelines to support the safe and reliable transport using U.S. pipelines. Federal regulations at 49 CFR Part 192 establish minimum safety requirements for pipeline facilities and the transportation of hydrogen using pipelines.

The Center for Hydrogen Safety (CHS), operating under the American Institute of Chemical Engineers, is a resource for strengthening safety knowledge and training. The center was formed in 2019, drawing upon decades of member's experience in working with hydrogen in petroleum refining and chemical processes. CHS has developed resources for training employees as well as first responders.[138]

The American Society of Mechanical Engineers (ASME) has developed a consensus design standard for hydrogen pipelines and plant piping in a document called ASME B31.12. The latest edition was published in 2019. As hydrogen pipelines have been recognized as a critical part of the energy transition, ASME members recently voted to update ASME B31.8 to address hydrogen pipelines and retire B31.12.[139]

Standards for composite pipe have been developed by the American Petroleum Institute (API) and the American Society for Testing and Materials (ASTM), including API 15S and ASTM Standard F2896-11. PHMSA has recently approved composite pipe in several segments for gas service under special permits. However, PHMSA, industry, and interested stakeholders should work together to develop safety standards specific to transport hydrogen using composite pipe. Ideally, the permits would be issued using PHMSA's normal process rather than as special permits, which take longer. The B31 Committee of ASME has issued Code Case 200 that specifies how composite pipe and appurtenances can be used in hydrogen service.

4. Research, Development, and Demonstration Activities

A variety of research, development, demonstration, and deployment initiatives are currently underway in the United States and around the world to evaluate the role of existing energy infrastructure in supporting the hydrogen energy transition. Figure 3-28 depicts the ongoing research and demonstration being conducted to address these challenges.

136 Topolski et al., October 2022.

137 Flame ionization detectors detect hydrocarbons by burning them in a hydrogen/air mixture. The ions formed by the flame then pass through a detector. FID technology does not work for inorganic molecules such as H_2. Additionally, H_2 does not have an infrared or other easily exploitable electromagnetic signature that would enable the use of optical technologies.

138 CHS's website provides a link to a Hydrogen Tools Portal developed by the Pacific Northwest National Laboratory through support from the DOE's Office of Energy Efficiency and Renewable Energy.

139 American Society of Mechanical Engineers. 2024. "Hydrogen Piping & Pipelines. B31.12-2023." https://www.asme.org/codes-standards/find-codes-standards/b31-12-hydrogen-piping-pipelines.

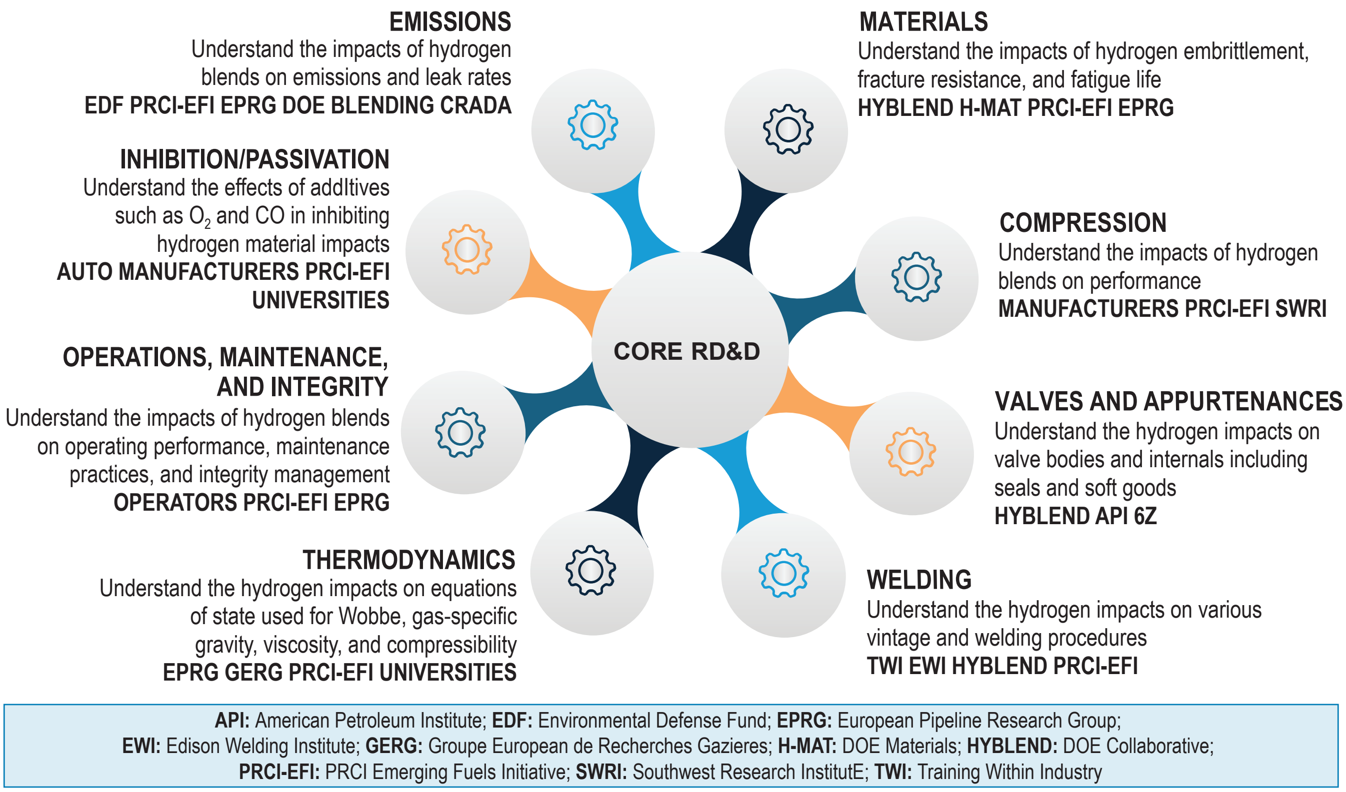


Figure 3-28. *Ongoing RD&D on the Impacts of Hydrogen in U.S. Pipelines*

According to a NREL technical assessment report on the feasibility of hydrogen blending into the existing natural gas infrastructure, "Hawai'i Gas, New Jersey Natural Gas, and SoCalGas are the only U.S. utilities to have successfully demonstrated blending of hydrogen into natural gas transmission and/or distribution lines."[140] According to the same report, Hawai'i Gas has been successful in using a blend of hydrogen in their natural gas network with an average of around 12% hydrogen (by volume) sourced from an SNG production plant since the 1970s in Oahu's natural gas network. The transmission portion of the system operates at 400 psi, a relatively low pressure for transmission, therefore a low-pipeline stress level. The distribution parts of the system operate at 12 psi, which is representative of a low-pressure distribution system. Prior to leveraging hydrogen from its SNG production facility, Hawai'i Gas has been successfully transporting town gas, a gas mixture containing up to 50% hydrogen (by volume), within sections of their transmission and distribution network for decades. In 2021, New Jersey Natural Gas began injecting relatively small volumes (65 kg/day, representing less than 1% hydrogen blend by volume in the natural gas system) of hydrogen into an 8-inch, 60 psi distribution line. In 2016, SoCalGas, along with NREL and the University of California Irvine (UCI), partnered to develop a smaller-scale blending demonstration facility at the UCI campus. This study concludes that UCIs 13-MW gas turbine could handle natural gas mixtures with up to 3.8% hydrogen by volume with no discernible impacts to operations.[141]

The DOE-funded HyBlend initiative seeks to develop and demonstrate technologies and protocols for safely and cost-effectively blending hydrogen into the natural gas network. As part of that initiative, NREL, in collaboration with more than 20 industry, nonprofit, and academic partners, intends to focus on the development of technologies that can be used to blend LCI H_2

140 Topolski et al., 2022.

141 Topolski et al., 2022.

into the natural gas distribution system at levels of up to 20% by volume. HyBlend is evaluating material compatibility and operational issues with the use of existing transmission pipelines as well. This work includes developing sensors and other monitoring equipment to ensure the safe and reliable operation of blended LCI H_2 in natural gas pipeline infrastructure, as well as advanced materials and coatings to address corrosion and other concerns. The project also aims to address key technical challenges associated with blending LCI H_2 into the natural gas distribution system, such as the impact on pipeline infrastructure and the effect on the performance of natural gas-powered appliances and other equipment. The overall goal of the HyBlend initiative is to develop and demonstrate technologies that can be used to blend hydrogen safely and effectively into the natural gas systems, with the goal of reducing GHG emissions and improving system energy efficiency.

5. Global RD&D Initiatives

In the United Kingdom, the HyDeploy project sought to demonstrate that hydrogen could be blended into the existing natural gas distribution network. A test community was established at Keele University as part of this demonstration project, with 101 homes and 30 faculty buildings fed a blended mixture of natural gas and hydrogen. Domestic appliances were found to operate safely with a hydrogen blend of up to 28.4% by volume in the demonstration project.

The Pipeline Research Council International (PRCI) Emerging Fuels Initiative and its members are conducting research on the feasibility of using existing transmission infrastructure. Members common to both the HyBlend and PRCI research and development work are coordinating to maximize its effectiveness and timeliness. There are also joint industry projects that have efforts directed at evaluating certain pipeline materials and welding methods. Additional DOE funding would help advance the timeliness of the studies and accelerate the pace at which parts of the existing infrastructure are evaluated and ready to transport hydrogen/natural gas blends. Furthermore, DOE funding for field testing to validate theoretical and lab results will expedite the ability to use some of the existing pipeline infrastructure to transport and store hydrogen.

In the Netherlands, HyDelta is a research program intended to facilitate the large-scale implementation of hydrogen. HyDelta research areas include hydrogen safety, hydrogen in the gas grid, value chain and hydrogen admixing, economic aspects of the hydrogen system, hydrogen and transport assets, and social aspects of hydrogen.[142]

The European Hydrogen Backbone (EHB) initiative, led by a consortium of thirty-one energy infrastructure operators[143] in the EU, is working to accelerate hydrogen adoption as part of its renewable procurement targets and to develop greater energy security in the region. The EHB has proposed to develop a hydrogen backbone network of ~33,000 miles by 2040 and is expecting further growth after that. The EHB intends to, in part, repurpose natural gas infrastructure for hydrogen transport. The initiative is centered on the construction of a network of hydrogen pipelines capable of transporting hydrogen gas over long distances. The EU Hydrogen Backbone initiative reflects a growing recognition of the need to invest in hydrogen infrastructure and technologies required to support its widespread use.

The GET H_2 Nukleus project is part of a larger effort in multiple countries, including Germany and the Netherlands. That project envisions cross-border infrastructure connectivity, with approximately 81 miles of network from Lingen to Gelsenkirchen, providing consumers with non-discriminatory access.[144]

$H_2$1 North of England is a project in the United Kingdom that aims to demonstrate the feasibility of repurposing existing natural gas pipelines for the transport of hydrogen gas. The project is focused on the development of a network of hydrogen pipelines in the north of England, with the goal of establishing a hydrogen backbone in the region. The $H_2$1 North of England project is being led by Northern Gas Networks in partnership with Equinor and U.K. gas distributer

142 HyDelta. 2023. "Research Programme." https://hydelta.nl/research-programme.

143 The initiative is supported by a range of stakeholders, including gas utilities, pipeline operators, research institutions, and technology companies.

144 Open Grid Europe. 2024. "GET H_2-Starting Point for the European Hydrogen Economy." https://oge.net/en/hydrogen/our-hydrogen-projects/get-h2-nukleus.

Cadent.[145] The $H_2$1 North of England project is part of a broader effort to support the development of hydrogen as a clean and sustainable energy source in the United Kingdom.

The initiatives described above are expected to provide valuable insights into the technical and economic feasibility of blending hydrogen into existing natural gas pipelines for LCI H_2 transport, as well as the potential benefits and challenges of such a conversion.

C. Role of New LCI Hydrogen Infrastructure

Building new infrastructure allows for strategic placement of production facilities, storage sites, and distribution networks, thereby optimizing the transportation of LCI H_2 to demand centers. The development of new LCI H_2 infrastructure can also enable the development of local or regional LCI H_2 hubs where leveraging existing infrastructure for capacity expansion may be infeasible. Different demand sectors (transportation, industry, power generation, and residential and commercial heat users) may have specific infrastructure requirements. Building new infrastructure allows for customization and optimization to meet the specific needs. New LCI H_2 infrastructure development can also drive the deployment of latest technological advancements and design improvements specifically tailored for LCI H_2, allowing for greater efficiencies in hydrogen transportation, storage, and delivery.

1. Technical Aspects of New LCI Hydrogen Infrastructure Development

Development of new dedicated LCI H_2 infrastructure will require work to be conducted and completed by various research and development organizations, as well as consensus standards development across organizations, including API, ASME, ASTM, and others. The work will ensure that materials will be suitable for service.

Conventional and lined pipe: New transportation infrastructure can be designed and constructed using ASME B31.8 after the standard is updated to include hydrogen and natural gas blends, which should allow for operation at stress levels similar to natural gas. Pipe manufacturers have developed and continue to refine alloying and manufacturing processes to reduce the impact of embrittlement and increase the fracture toughness of line pipe. The API Subcommittee 5 on lined pipe is considering revisions to the standard for hydrogen blends coordinating with the HyBlend Cooperative Research and Development Agreement and Hydrogen Materials Consortium (H-MAT) programs.

Welding: Welds for new hydrogen pipelines should be made using welding consumables and procedures suitable for hydrogen service. Once updated, ASME B31.8 will provide requirements for welding pipelines that transport hydrogen and hydrogen blends. This update will draw on API STD 1104—Welding of Pipelines. API formed a Hydrogen Fuel Gas Pipelines Task Group to review the current edition and identify areas of improvement and suitability for hydrogen service. The task group is coordinating with efforts being undertaken in HyBlend and PHMSA, through their RD&D program, and drawing on experts from the United States, Europe, and Australia, including The Welding Institute, where there are operator and joint industry projects addressing welding in hydrogen service.

Compression: As described earlier, compression demand and corresponding temperatures both increase with hydrogen concentration when considering compression at constant pressure rise and inlet temperature.[146, 147] The increase in compression work and the temperature rise can be compensated for during new compression design. Reciprocating compressors are a proven technology for hydrogen service, having been applied in industrial gas and petroleum refining. Centrifugal compression can also be considered for larger diameter/capacity systems.

145 Northern Gas Networks. 2020. "$H_2$1 North of England–National Launch." January 30, 2020. https://www.northern-gasnetworks.co.uk/event/h21-launches-national/.

146 Kurz, R., Lubomirsky, M., and Bainier, F. 2011. "Hydrogen in Pipelines: Impact of Hydrogen Transport in Natural Gas Pipelines." https://asmedigitalcollection.asme.org/GT/proceedings-abstract/GT2020/84201/V009T21A001/1095159.

147 Zabrzeski, Ł., Janusz, P., Liszka, K., Łaciak, M., and Szurlej, A. 2019. "Hydrogen-Natural Gas Mixture Compression in Case of Transporting through High-Pressure Gas Pipelines." *IOP Conference Series: Earth and Environmental Science.* 214 (January): 012137. https://doi.org/10.1088/1755-1315/214/1/012137.

Measurement and sensors: With a new pipeline, measurement technology can be specified for hydrogen service. As discussed in Section VII.B, measurement technologies that are suitable for natural gas are generally suitable for use in hydrogen service with minor modifications.

Valves and fittings: Valves and fittings can be specified with tighter tolerances to minimize leakage. API has formed a task group to develop a new standard for hydrogen gas service that will be known as API 6Z. The British Valve and Actuator Association has a Hydrogen Technical Expert Group working on hydrogen applications and will coordinate with the work on API 6Z. Sealing materials and other soft goods in valves and fittings can be specified specifically for hydrogen service.

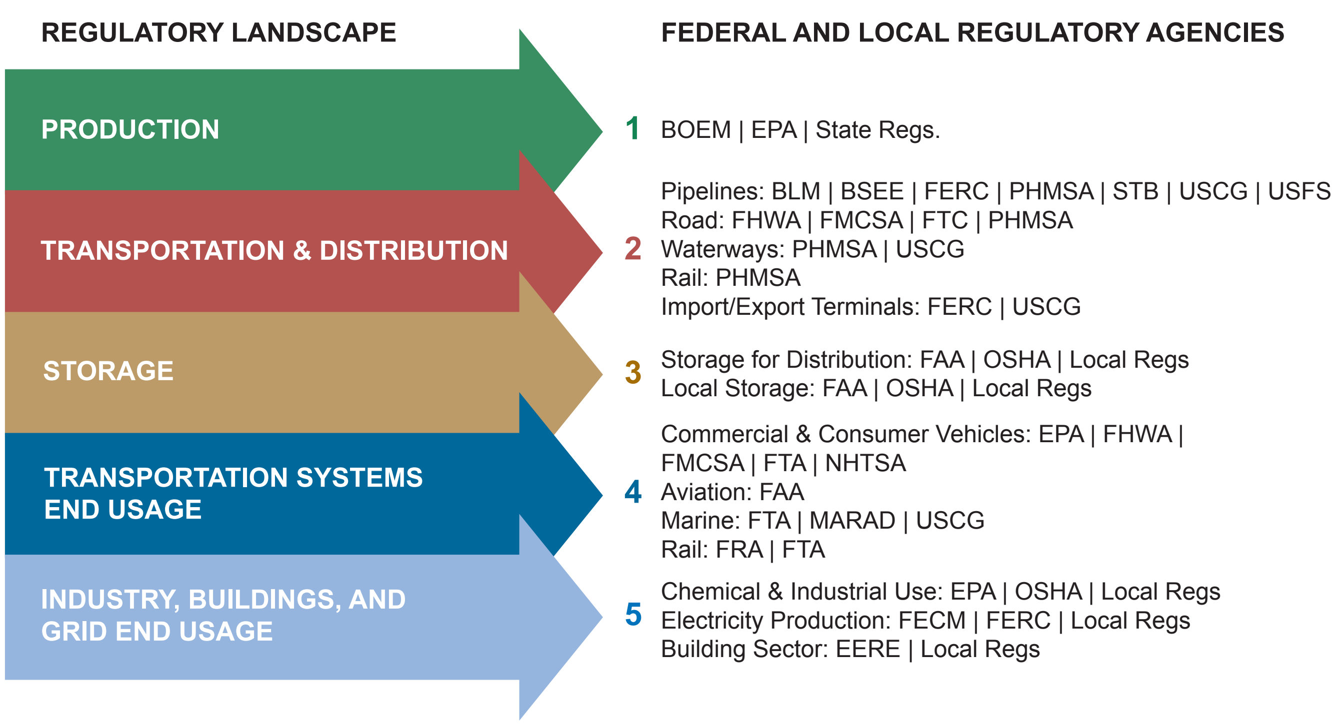
D. Challenges for LCI Hydrogen Infrastructure Development

1. Hydrogen Infrastructure Permitting

Permitting LCI H_2 and associated supporting infrastructure projects (CO_2 pipeline and storage infrastructure in the United States) can present several key challenges. These challenges can vary depending on the project's location, scale, and the specific regional and local regulatory environment. Navigating through the complexities, and sometimes overlapping requirements, can be challenging for infrastructure development. When there is a lack of clear guidelines and a specific regulatory framework, it can lead to a multiyear permitting approval process. Multiple agencies will be involved in the permitting process for hydrogen infrastructure development in the United States, but will vary depending on the specific project's location and scope (a function of the many hydrogen transport, storage, and delivery pathways) as shown in Figure 3-29.

PHMSA regulates the safety of pipelines transporting hazardous materials, including hydrogen. Depending on the project, developers may need special permits (or special permit modifications) from PHMSA. Environmental permits or approvals are required to assess and mitigate potential environmental impacts of the project. These can potentially include (to name a few):

- NEPA
- Clean Water Act (CWA) Section 404 Permit for wetland impacts



Source: DOE, 2023.

Figure 3-29. *Agency Oversight for Infrastructure Permitting*

- Clean Air Act Permit for air emissions
- National Pollutant Discharge Elimination System
- Permit for water discharges, Stormwater Pollution Prevention Plan (SWPPP) Permit

If the hydrogen infrastructure project involves crossing navigable waters or wetlands, permits from the U.S. Army Corps of Engineers may be necessary under the CWA and the Rivers and Harbors Act. PHMSA enforces regulations related to pipeline safety. Depending on the project, developers may need permits or approvals from the DOT related to pipeline construction and operation.

The lack of a centralized governing authority to streamline the permitting governance adds further complexities. For example, no federal agency has attempted to regulate the siting, construction, rates, and services of interstate hydrogen pipelines, and it is unclear which, if any, federal statute(s) would apply to new projects. It is uncertain whether the current regulatory framework (without a central governing authority) will be able to accommodate the expansion of the existing (and mostly regional) hydrogen pipeline infrastructure network to other parts of the country.

Permitting hydrogen infrastructure projects often involves coordination among multiple agencies at the federal, state, and local levels. Ensuring effective communication, collaboration, and alignment among different agencies can be challenging and may result in delays or complications during the permitting process. Demonstrating compliance with technical standards, safety regulations, and addressing concerns related to hydrogen transport, storage, and distribution can pose challenges for permitting authorities. The complexity of the current permitting process can be costly, requiring significant resources for studies, assessments, and consultation. Delays in the permitting process can impact project timelines and increase overall costs, potentially affecting project viability and financing. Large-scale infrastructure projects could also face opposition from local communities driven by public perception, concerns about safety, land use, and potential environmental and community impacts. Reforms designed to provide a clear permitting path could unlock strategic benefits to the environment, communities, and the economy from the rapid development of LCI H_2 infrastructure in the United States. See Chapter 6: Policy for additional insights and associated recommendations to address the permitting challenges.

2. Carbon Dioxide Transportation and Storage Infrastructure Permitting

There are additional considerations associated with permitting CO_2 pipeline transportation and permanent storage of transported CO_2 in subsurface geologic formations. CCS infrastructure development in the United States has been primarily driven to support enhanced oil recovery operations. To support the production of LCI H_2 from natural gas (with post-combustion carbon capture technologies), further development and expansion of CO_2 transportation and storage infrastructure will be needed.

In addition to leveraging the existing CO_2 pipelines and storage facilities to the extent possible, integrating the development of new open-access CO_2 transport and storage infrastructure will be essential for cost-effective and scaled deployment to support LCI H_2 production.

Various federal and state agencies have developed specific regulatory and permitting requirements to ensure the safety of CO_2 transportation and storage systems. The current regulatory framework (through multiple agencies) aims to ensure secure CO_2 transportation and storage. PHMSA has the authority to regulate CO_2 pipelines in the United States Under the Safe Drinking Water Act (SDWA), while the EPA has created specific regulatory and permitting frameworks to safeguard underground sources of drinking water (USDW) during injection and geologic storage of CO_2. For the injection of CO_2 into geologic storage facilities, the EPA has developed accounting protocols under the Greenhouse Gas Reporting Program. Regarding CO_2 pipeline and storage infrastructure, each state may also have its own set of rules and requirements for infrastructure development.

Permitting challenges related to transportation and storage can occur in the United States due to a variety of factors, resulting in a multiyear approval process for infrastructure development. Development of CO_2 transport and storage infrastructure projects requires obtaining various permits (such as environmental, land use, drilling, underground injection control, etc.) and complying with regulatory frameworks across federal, state, and local levels. Permitting complexities, including lack of standardized permitting processes across multiple jurisdictions and lengthy processing timelines, can all present challenges, leading to uncertainties and execution delays for project developers. It is therefore critical to design and implement a clear transportation and storage permitting framework, offering the certainty necessary to develop the needed infrastructure in a timely manner.

The development of CO_2 storage projects entails detailed site characterization and evaluation necessary to assess the suitability and safety of the storage site. This process involves studying geologic formations, subsurface structures, and hydrogeological conditions. Permitting challenges may arise due to the complexity and time required for site characterization and the need to demonstrate the long-term stability and containment of the storage reservoir. The EPA established requirements for the injection of fluids into subsurface formations under the SDWA through the Underground Injection Control (UIC) program. The UIC program's statutory mandate is to protect USDW, which is primarily accomplished by ensuring safe, long-term containment of the injected CO_2 streams and displaced formation fluid.

In 2010, EPA developed a Class VI UIC program, addressing well design and permitting processes, for the injection of CO_2 for storage in saline formations. The program was developed to provide near-term regulatory certainty for CO_2 geologic storage, promote consistent permitting approaches, and ensure that permitting agencies can meet their demands. The elements of the rulemaking were based on the existing UIC regulatory frameworks with modifications to address the unique nature of CO_2 injection for geologic storage. Class VI permitting is a procedural process and is initiated with a permit application to the EPA followed by subsequent review and comments processes before authorizing the necessary permits to drill injection wells. Issuing the authorization to drill, and ultimately to inject, CO_2 is highly project dependent on a multitude of factors, including length of time to drill, subsurface geology and its resemblance to the permit application, modeling of the area of review, and any other additional information as requested by the EPA. A lengthy backlog of carbon storage project applications remaining in the approval queue at the EPA has delayed the progress of development of a scaled CCS industry. Speeding up the permitting processes with timely review and approval of these Class VI UIC well applications will help enable the development of CO_2 storage infrastructure in an expeditious manner needed to support the LCI H_2 economy.

CO_2 storage infrastructure development could have long-term implications, including the responsibility for monitoring and ensuring the integrity of the storage site over decades. Permitting challenges may emerge in defining liability responsibilities, establishing monitoring protocols, and securing financial assurances for long-term site management and potential leakage mitigation. Therefore, addressing all the above challenges requires alignment of regulatory processes, establishing clear guidelines and standards, enhancing all stakeholder engagement, and providing regulatory certainty. Governments, regulatory agencies, and industry stakeholders are continuously working to address these challenges and to create a more supportive environment for the development of CO_2 transport and storage infrastructure.

3. Community Engagement

Community engagement plays a critical role in advancing the development of hydrogen infrastructure projects and can significantly impact the permitting process. API Recommended Practice (RP) 1185, published in March 2024, defines standards for community engagement, defining stakeholders, making initial contact, developing long-term relations, and environmental justice. Community engagement helps to build trust, incorporates community input, enhances project design, informs decision-making, strengthens relationships, and demonstrates social responsibility. Developers should proactively engage with the community throughout the permitting process to foster a collaborative and inclusive approach to project development. Engaging with the local community early in the process allows project developers to build trust and establish open lines of communication. It provides an opportunity to address concerns, share project details, and educate community members about the benefits and safety measures associated with hydrogen infrastructure. By actively involving the community, developers can work toward gaining acceptance and support for the project, reducing potential opposition and delays in the permitting process. Active community engagement during the permitting process ensures that decision makers in regulatory agencies and local governments are aware of community perspectives and concerns. Community input can influence the decision-making process, influencing permit approvals and conditions. Citizen participation in public hearings, comment periods, and community meetings provides decision makers with a comprehensive understanding of local sentiments and helps them make more informed and equitable decisions.

Effective community engagement fosters long-term relationships between developers and the community. By maintaining ongoing communication and involvement, developers can stay connected with the community throughout the project life cycle, beyond the permitting process. This continued engagement can support successful project implementation, facilitate ongoing monitoring and compliance, and create opportunities for collaboration and shared benefits. Engaging with the community demonstrates a commitment to social responsibility and sustainable development. Developers who actively involve the community in the permitting process show a willingness to listen, respond, and address community concerns. This proactive approach can enhance the project's reputation, improve stakeholder relationships, and contribute to the long-term success of the hydrogen infrastructure project (see Chapter 7: SCI & Safety for additional information regarding community engagement practices).

VIII. ROLE OF HYDROGEN HUBS

A. Introduction

LCI H_2 hubs will serve as the foundation for a U.S. clean hydrogen network, which will significantly contribute to the decarbonization of multiple sectors of the economy, including heavy industries and heavy-duty transportation sectors. To facilitate long-term capacity expansion and scaling, LCI H_2 hub developers should consider a variety of hub development pathways, ranging from programmatic to market-based; a variety of hub structural types; and an integrated planning strategy with a market-driven approach.

The LCI H_2 hub in this study is defined[148] as an integrated infrastructure solution that supports the production, processing, transportation, storage, and delivery of LCI H_2 to various end uses via local or regional LCI H_2 infrastructure ecosystems. These ecosystems are networks of LCI H_2 producers, potential end-use consumers, and connective infrastructure located close to supply and demand. They demonstrably aid the achievement of the clean hydrogen production standards[149] and support:

- The demonstration of production, processing, delivery, storage, and end use of clean hydrogen
- The development of a national clean hydrogen network to facilitate a clean hydrogen economy

IIJA allocates $8 billion in funding for the development of at least four regional clean hydrogen hubs addressing hydrogen feedstock, end use, and geographic diversity as part of the above listed criteria.[150, 151] On October 13, 2023, the DOE announced $7 billion of that funding to launch seven regional clean hydrogen hubs (H_2Hubs) selected from more than 30 applications.[152]

148 IIJA defines the term "regional clean hydrogen hub" as "a network of clean hydrogen producers, potential clean hydrogen consumers, and connective infrastructure located in close proximity."

149 Developed under Section 822(a) of the Energy Policy Act of 2005 (EPAct 2005), as amended by Section 40315 of IIJA.

150 DeFazio, Peter A. 2021. "H.R.3684-117th Congress (2021-2022): Infrastructure Investment and Jobs Act." U.S. House of Representatives. November 15, 2021. https://www.congress.gov/bill/117th-congress/house-bill/3684/text.

151 Feedstock diversity implies hydrogen produced using multiple feedstocks (fossil fuels, nuclear, and renewable energy); end-use diversity implies hydrogen uses across multiple end-use applications, including electric power generation, industries, residential and commercial heating, and transportation; geographic diversity implies no hydrogen hub in the same region as another.

152 DOE. 2023. "Regional Clean Hydrogen Hubs Selections for Award Negotiations." https://www.energy.gov/oced/regional-clean-hydrogen-hubs-selections-award-negotiations.

The LCI H_2 hubs definition for this study incorporates the IIJA hydrogen hubs definition and further expands the hub development framework to account for a wide range of scales, architectures, and development paths. For the sake of clarity, this study will refer to the regional clean hydrogen hubs supported by IIJA funding as "IIJA-sponsored regional hubs."

Benefits: The development of LCI H_2 hubs in the United States is critical to the scaling of the hydrogen economy because it facilitates significant investment in LCI H_2 infrastructure, drives down cost to produce and distribute LCI H_2, achieves GHG emissions reductions, integrates renewable energy sources, promotes multistakeholder collaboration, optimizes supply chains, fosters economic development, supports energy security, and facilitates learning and innovation. In addition, the potential LCI hub developments provide a quicker, more efficient path to market scale and hasten the development of a transparent and liquid market for LCI H_2 as tradable commodity, a necessary element of a clean hydrogen economy.

Regional supply and demand factors, renewable energy resource potential, availability of existing energy and supporting infrastructure (access to natural gas network, electric grid infrastructure, water, CO_2 transportation and storage facilities, etc.), geographical characteristics, labor and community resources, and technoeconomic considerations all influence the choice and type of LCI H_2 hub development in the United States. Understanding regional dynamics allows for the development of customized, efficient, flexible, and resilient LCI H_2 infrastructure solutions to meet regional supply and demand requirements, while also enhancing the growth and expansion of the LCI H_2 economy in each region.

The creation of LCI H_2 hubs across the United States could foster regional collaboration and cooperation among governments, industry, and research institutions. Regions can accelerate the development and deployment of LCI H_2 technologies by forming partnerships and sharing resources, knowledge, and expertise, allowing them to make rapid progress toward scaling the hydrogen infrastructure. The scale and magnitude of societal (community, environmental justice) and environmental (local air quality, GHG emissions) impacts will depend on the type of integrated development, as well as the development pathway for a given hub. Hub development offers the opportunity to create what the U.S. National Clean Hydrogen Strategy and Roadmap refer to as "place-based opportunities for equity, inclusion, and sustainability."[153] This will only occur when communities, labor, environmental stakeholders, and other stakeholders have a seat at the table to address the necessary planning framework to develop integrated hub ecosystems.

LCI H_2 infrastructure, including transportation, storage, and delivery, will be critical enablers in the United States, supporting a variety of LCI hub archetypes. For example, the development of large-scale LCI H_2 backbone systems that includes pipelines and/or storage resources may serve as anchors for the development of infrastructure-centric LCI H_2 hubs. Transportation, storage, and delivery infrastructure that supports multiple customers will enable the success of large-scale LCI H_2 hubs, where a diverse set of dispersed producers support large LCI H_2 hubs, which in turn support higher volumetric demand for a variety of end-use sectors.

Development pathways: The development of LCI H_2 hubs, in response to IIJA funding for regional clean hydrogen hubs, represents one of three general pathways to hub development, each supported by varying levels of government funding and incentive support mechanisms. As illustrated in Figure 3-30, the three pathways include:

- **Intentional support** entails strong governmental involvement in selecting and supporting funding for LCI H_2 hub development. The IIJA H_2Hubs program represents the prime example of this hub development pathway. The processing timelines for identifying, selecting, and funding specific hubs may result in longer lead times for hub development. For example, the four-phase stage-gate process for funding the DOE regional hydrogen hubs may result in hub ramp-up and operation commencing between 2030 and 2035. This pathway-to-hub

153 DOE. 2023. "U.S. National Clean Hydrogen Strategy and Roadmap." https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap.

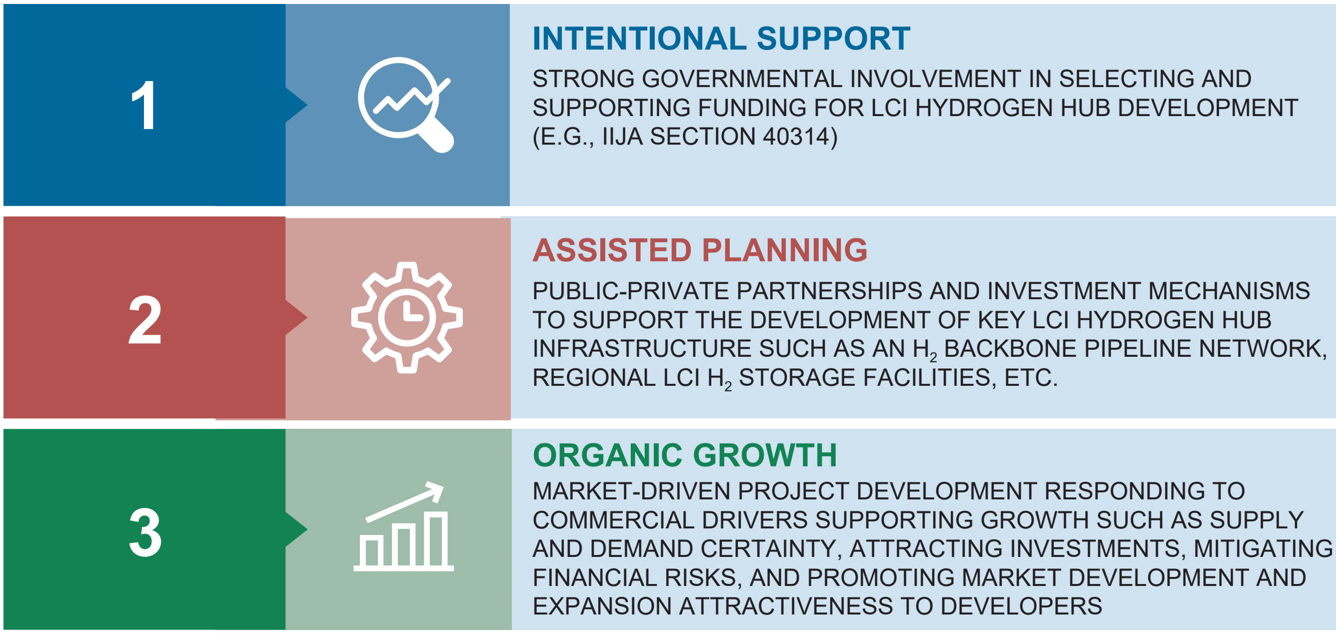


Figure 3-30. *Potential Pathways for LCI Hydrogen Hub Development*

development may face additional compliance/accountability requirements and constraints (e.g., the community benefit requirements associated with DOE funding for IIJA-sponsored regional hubs).

- **Assisted planning** entails public-private partnerships and investment mechanisms for the development of key components (a hydrogen backbone pipeline network or regional LCI storage facilities) in support of LCI H_2 hub infrastructure. Secured or direct loans, or loan guarantees, similar to those available through CIFIA[154] for CO_2 infrastructure development funding, would help stimulate commercial development interests and public-private partnerships.
- **Organic growth** is a pathway characterized by integrated project development in response to financial incentives (the Section 45V tax credit included in the IRA rather than project-specific funding support). Project development will respond to a variety of commercial drivers, including creating a market with supply and demand certainty. Attracting investments, mitigating financial risks, and promoting market development and potential expansion are easier with supply and demand certainty. In the Expansion and At-Scale phases, the organic growth mechanism will most likely be the dominant form of LCI hydrogen hub development.

B. Phases of LCI Hydrogen Hub Development

Scaling LCI H_2 hubs between now and 2050 can be accomplished in three illustrative phases that consider the gradual expansion of infrastructure, technological advancements, market development, and sustained policy support.

1. Activation Phase

Accelerated by the IRA hydrogen tax credits for production (45V), storage (ITC), and permanent CO_2 storage (45Q), IIJA funding opportunities, along with a streamlined permitting process, the shift to LCI H_2 will primarily occur where supply and demand are colocated and utilize preexisting and new hydrogen infrastructure to support regional pockets of industrial demand centers. During this phase, the establishment of LCI H_2 hub demonstration projects in specific regions will be critical, with a focus on the development of critical connecting infrastructure, evaluation of metallurgical and infrastructure integrity, and

154 DOE. 2022. "CIFIA Loans for Carbon Dioxide Transportation Infrastructure." https://www.energy.gov/sites/default/files/2022-10/LPO_CIFIA_Guidance_Document_FINAL_2022.10.05_0.pdf.

validation of commercial business models. Collaborations between governments, industries, and research institutions help to develop these demonstration projects. Investing in research and development initiatives during this phase to advance LCI H_2 production, transportation, storage, and end-user utilization technologies will aid in addressing key research gaps and further advancing new technology pathways.

Meanwhile, the seven regional hubs funded by the IIJA will proceed through the DOE four-phase stage-gate process, likely initiating construction during the Activation phase. The complexity of the sponsored hub developments, the challenges of navigating complex federal, state, and local permitting processes, coordination, and timing of interdependent value chain project development, may push regional hub development beyond the timelines anticipated in the DOE Clean Hydrogen Hub Funding Opportunity Announcement (FOA).

During this phase, the LCI H_2 hub infrastructure gradually expands organically to form nascent regional networks that integrate centralized and distributed hubs. This expansion is primarily driven by regional demand that is supported by strategically established production facilities, transportation pathways, location-specific storage systems, and last mile delivery networks. Creating supply-demand certainty in the marketplace will help foster collaborative partnerships and strengthen longer-term LCI H_2 offtake agreements. It is critical to address and clear potential roadblocks (e.g., permitting bottlenecks) to enable commercial development during the Activation phase.

2. Expansion Phase

A regional LCI H_2 hub system (likely interstate) will begin to materialize, integrating a large network of diverse LCI H_2 production facilities that will provide large volumetric flows to demand centers enabled by a diverse portfolio of connecting infrastructure. As regionally dispersed LCI H_2 hubs emerge to serve multiple demand sectors during this phase, the development of intrastate and/or interstate regional pipelines connecting more producers and offtakers will be required to connect the growth in LCI H_2 supply and demand. A locality's geographical characteristics can influence the type of LCI H_2 hub that is integrated into the larger regional network. Coastal regions, for example, may focus on developing hubs with port access for exporting hydrogen in the form of liquid carriers (ammonia or LOHC) and would drive large volumetric flows of hydrogen from regional networks. An integrated regional hub provides opportunities for localized LCI H_2 hubs near coastal regions with deep seaport facilities to investigate LCI H_2 export opportunities by establishing shipping or pipeline infrastructure for hydrogen transportation to neighboring countries or overseas markets. The formation of international partnerships and trade agreements to promote hydrogen exports will require hydrogen to meet importer standards. In this scenario, ports become a logical infrastructure-centered hub serving both domestic and international demand.

The seven IIJA-funded regional hubs are expected to ramp up and begin operations during the Expansion phase. Successful implementation of the IIJA Regional Hub program will serve as a driver of additional organic development, drawing private sector capital into regions with supportive LCI H_2 infrastructure.

The regional LCI H_2 hub network may begin to promote cross-border collaborations to leverage regional strengths and resources that span national borders to meet the hub network's high volumetric demand. Public-private partnerships in hydrogen infrastructure development may be particularly important in supporting large-scale regionally interconnected LCI H_2 hub deployments. Such partnerships can attract additional capital by establishing financing mechanisms, venture funds, and bilateral or multilateral arrangements with financial institutions to help deliver the large capital investments needed in the Expansion phase.

3. At-Scale Phase

During the At-Scale phase, a mature and highly integrated national LCI H_2 hub network will emerge across the United States, with the goal of providing nationwide coverage of hydrogen infrastructure. Ultimately, a nationwide hydrogen infrastructure network will enable access to LCI H_2 across all demand sectors and regions, as well as support fully mature export markets. With widespread emissions reductions required to meet U.S. decarbonization targets by 2050, all regions in the United States can reap decarbonization benefits from an integrated national hydrogen hub network. The LCI H_2 hub network could be fully integrated into the electric grid and natural gas infrastructure as part of sector coupling during this phase, optimizing the use of hydrogen for electricity generation, grid balancing, and residential and commercial heating. By 2050, the United States should take a leadership role in strengthening international collaborations to align standards, share best practices, and offer support to accelerate global LCI H_2 hub expansion. The U.S. will have the required innovation, expertise, and know-how to engage in knowledge exchange and collaborative projects with other countries to help the global LCI H_2 economy grow.

C. LCI Hydrogen Hub Archetypes

LCI H_2 hubs are an essential component of supporting a hydrogen economy at-scale. They serve as integrated frameworks that facilitate the production, transport, storage, and delivery of hydrogen to meet varying end-user demands. A mix of hub development archetypes through intentional, assisted, and organic growth would enable an integrated LCI hydrogen hub architecture.

The large-scale regional LCI H_2 hubs driven by IIJA funding represent a critical piece of a U.S. clean hydrogen economy foundation but could have longer lead times for development. Smaller-scale subregional hubs centered around supply, demand and transportation/storage infrastructure and leveraging financial incentives present in the Section 45V tax credit will fill out the diverse hub architecture and, perhaps more quickly than planned, regional hub development. In response to the DOE FOA, there were 79 hub concept papers and approximately 30 applications eventually submitted for consideration. Ultimately, only seven hub proposals were selected. However, the rest are not likely to simply disappear. The concepts, relationships and agreements that developed as coalitions prepared to respond to the FOA will more than likely foster the growth of multiple (albeit conceptually morphed) LCI hub developments outside the DOE funding process.

A diversified portfolio of hub archetypes, with its unique characteristics and risks as illustrated in Figure 3-31, emphasizes the need to recognize the possible diversity of potential hub developments in the United States beyond large-scale IIJA-funded regional hubs. For example, a demand-centric hub focuses on meeting the hydrogen demand of specific regions or industries and can help create a market pull for LCI H_2. This incentivizes the development of supply-centric hubs to meet the scalability needed for a reliable and adequate supply of hydrogen to the demand centers. The infrastructure-focused hub archetypes help bridge the gap between supply and demand. They play a critical role in balancing the spatial disparities between hydrogen supply and demand, allowing for a wider geographic reach of the hydrogen economy. By integrating these archetypes in a regional ecosystem, an interconnected hydrogen ecosystem can be established, ensuring an efficient, scalable, market-driven growth for long-term viability. Effective integration of hub archetypes into the broader infrastructure development framework requires close collaboration among various stakeholders, including government agencies, industry players, research institutions, and communities. By leveraging these synergies, the hub infrastructure development framework can enhance the long-term economic viability and sustainability of an LCI H_2 economy.

1. Gulf Coast Region: Reducing Emissions with Existing Hydrogen Infrastructure

The Gulf Coast region has the potential to use its existing hydrogen production facilities to meet local LCI H_2 demand. Decarbonizing the existing carbon-intensive hydrogen production to meet regional demand will help reduce emissions from the Gulf Coast industrial complex and serve as a locus for incremental LCI H_2 production. Currently, the Gulf Coast region and the western United States have the highest demand for hydrogen.[155] The Gulf Coast region has a high concentration of centralized hydrogen production facilities, including 33 refineries, 27 merchant

155 Regional hub proposals from both the Gulf Coast region and California were both among the seven applications selected for funding through the IIJA Regional Clean Hydrogen Hubs program.

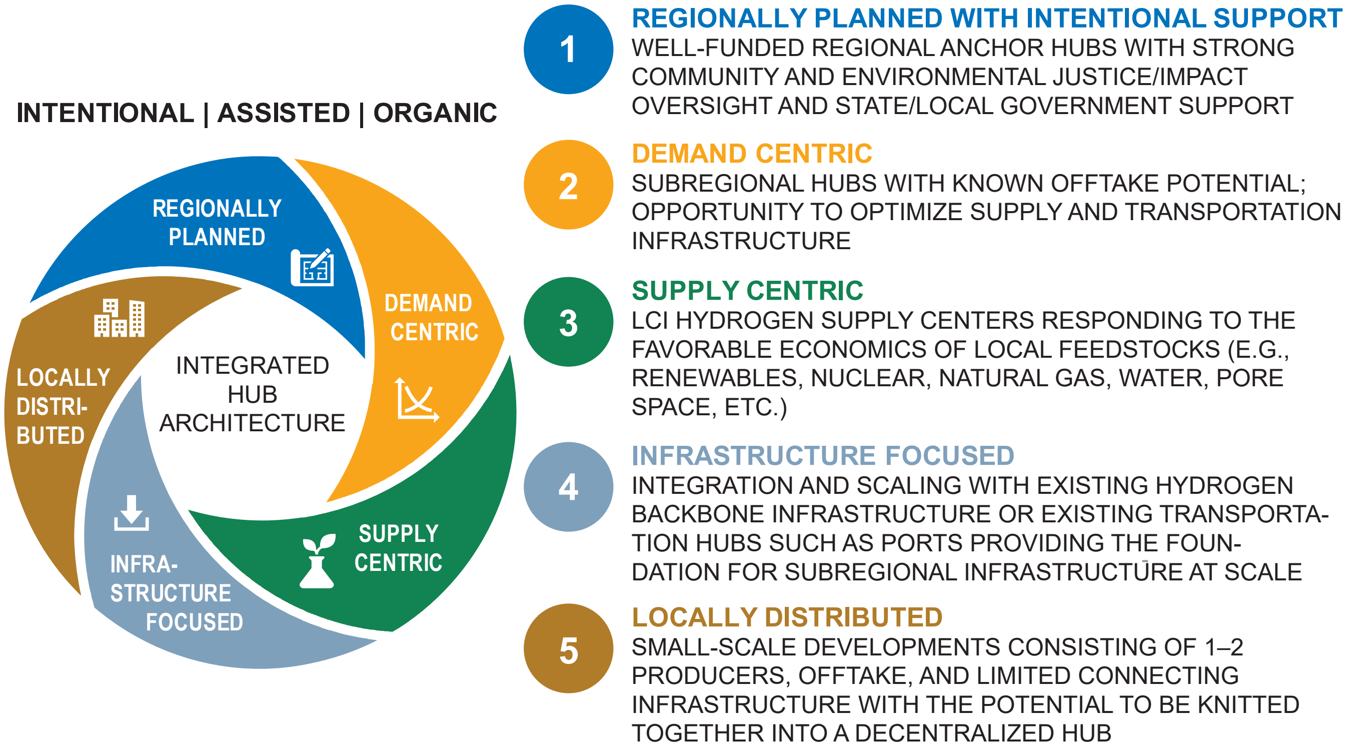


Figure 3-31. *A Mix of Hub Development Archetypes Through Intentional, Assisted, and Organic Growth*

hydrogen production facilities, and 10 ammonia production plants.[156] The network of hydrogen pipelines connecting merchant production facilities to refineries and industrial facilities along the Gulf Coast region makes it a strong regional supply and demand center for LCI H_2 hub development. In addition, the Gulf Coast LCI H_2 hub would be able to use existing CO_2 transport and storage infrastructure to transport and store CO_2 recovered from retrofitted SMR-based hydrogen production facilities, significantly reducing required infrastructure investment that would otherwise be needed to retrofit similar facilities with supporting CO_2 transport and storage facilities.

As illustrated in Figure 3-32, the Gulf Coast region serves as a potential LCI H_2 demand center for a variety of industrial end-use applications (industrial heat, chemical processing, and the production of synthetic fuels and biofuels, to name a few). Regions with established refining capacity and infrastructure (such as the U.S. Gulf Coast) could be home to future synthetic and biofuels production, creating demand for LCI H_2 fuel and feedstock. With an abundance of resources—wind, solar, subsurface storage space, and natural gas—to support a variety of LCI H_2 production methods, as well as strategic access to domestic and international hydrogen markets via deepwater ports, the Gulf Coast region has the potential to develop a large-scale LCI H_2 hub network supporting a diversity of supply resources to meet a large and diverse hydrogen end-user demand. The keys to unlocking this potential will be 1) a continued drive toward cost parity with carbon-intensive hydrogen production and 2) policies to stimulate offtake of LCI H_2 until cost parity is reached.

2. California: Diverse, Renewables-Based Hydrogen Economy

California is at the forefront of the clean energy transition. As part of its climate commitment, California set GHG emissions reduction goals to achieve carbon neutrality by 2045. California also requires 90% renewable and zero-carbon energy

156 Industrial Innovation Initiative. 2024. "The Landscape of Clean Hydrogen." https://industrialinnovation.org/resources/the-landscape-of-clean-hydrogen/.

sources as part of the state's electricity generation mix by 2035. California's ZEV policies, such as the Low Carbon Fuel Standard, Advanced Clean Transit rules, and Innovative Clean Transit Requirements provide significant regional competitiveness and policy advantages for the development of necessary infrastructure to meet future LCI H_2 demand. That infrastructure can support the FCEV transportation market, including light-, medium-, and heavy-duty trucking and bus fleets. The California Energy Commission has identified LCI H_2 (produced directly from renewable feedstocks) as a key enabler in supporting hard-to-abate industrial sectors, transportation markets, and electric grid reliability needs as part of California's clean energy transition.[157]

Currently, California's hydrogen production and demand can be attributed to five merchant hydrogen production facilities within its borders. Those facilities support 11 oil refineries, while also supplying the hydrogen FCEV market. As part of the California LCI H_2 hub, transitioning the state's refineries to leverage LCI H_2 for refining and process heating could provide immediate transition potential by replacing unabated fossil fuel-based hydrogen (see Chapter 5: Demand for a discussion on the role of LCI H_2 for refining).

As California expands its renewable energy generation capacity through progressive state policies and incentives, the development and integration of LCI H_2 produced by electrolysis offers great opportunity. California Hydrogen Hub proponents envision decarbonization potential across multiple end users, including transportation, port, and marine applications, and industrial, as illustrated in Figure 3-33. The California LCI H_2 hub is well-positioned to support the light-, medium-, and heavy-duty transportation sectors by expanding the use of LCI H_2. California is already at the forefront of hydrogen refueling station infrastructure development (described in Section IV.G of this chapter), with a network of 58 HRS across the state.[158] To help decarbonize

157 Regional hub proposals from both the Gulf Coast region and California were both among the seven applications selected for funding through the IIJA Regional Clean Hydrogen Hubs program.

158 Hydrogen Fuel Cell Partnership. 2024. "By the Numbers: FCEV Sales, FCEB, & Hydrogen Station Data." https://h2fcp.org/by_the_numbers.

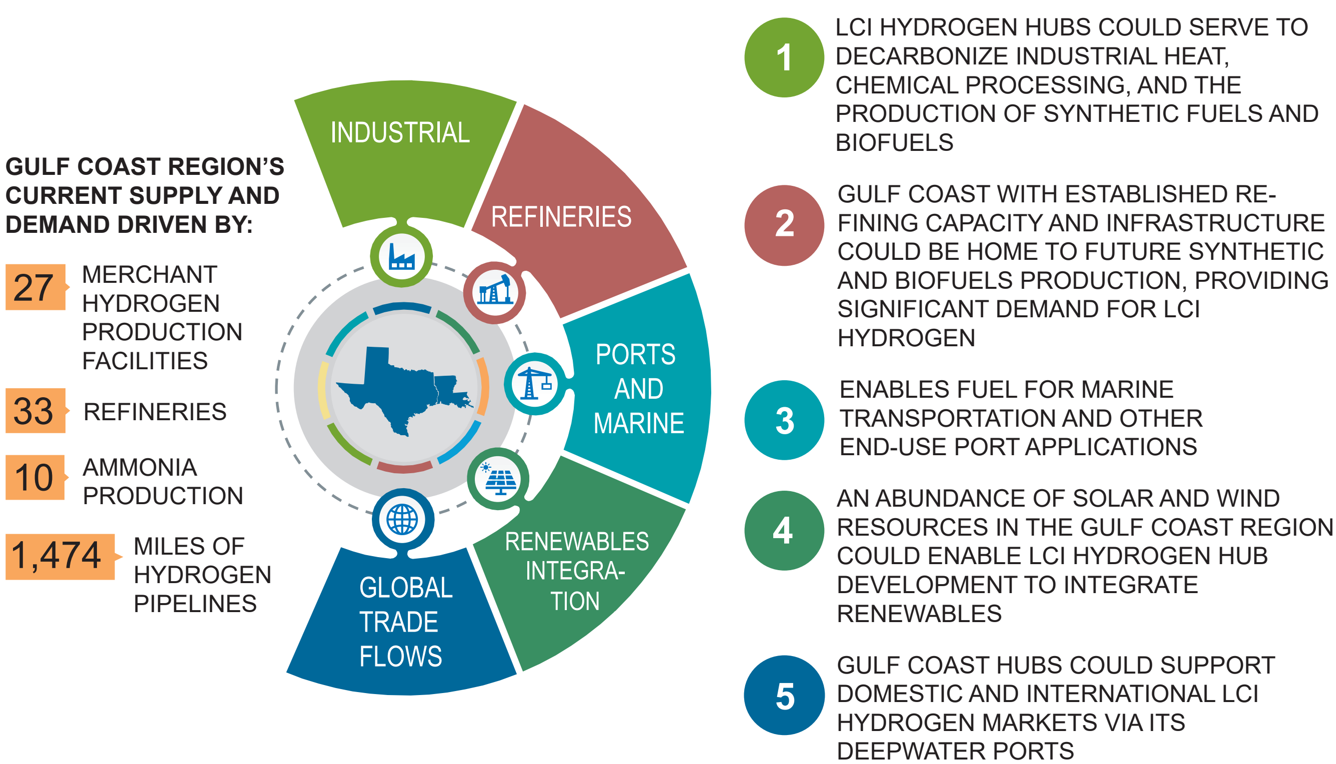


Figure 3-32. *Gulf Coast Region Sectoral Opportunities for LCI Hydrogen Hub Development*

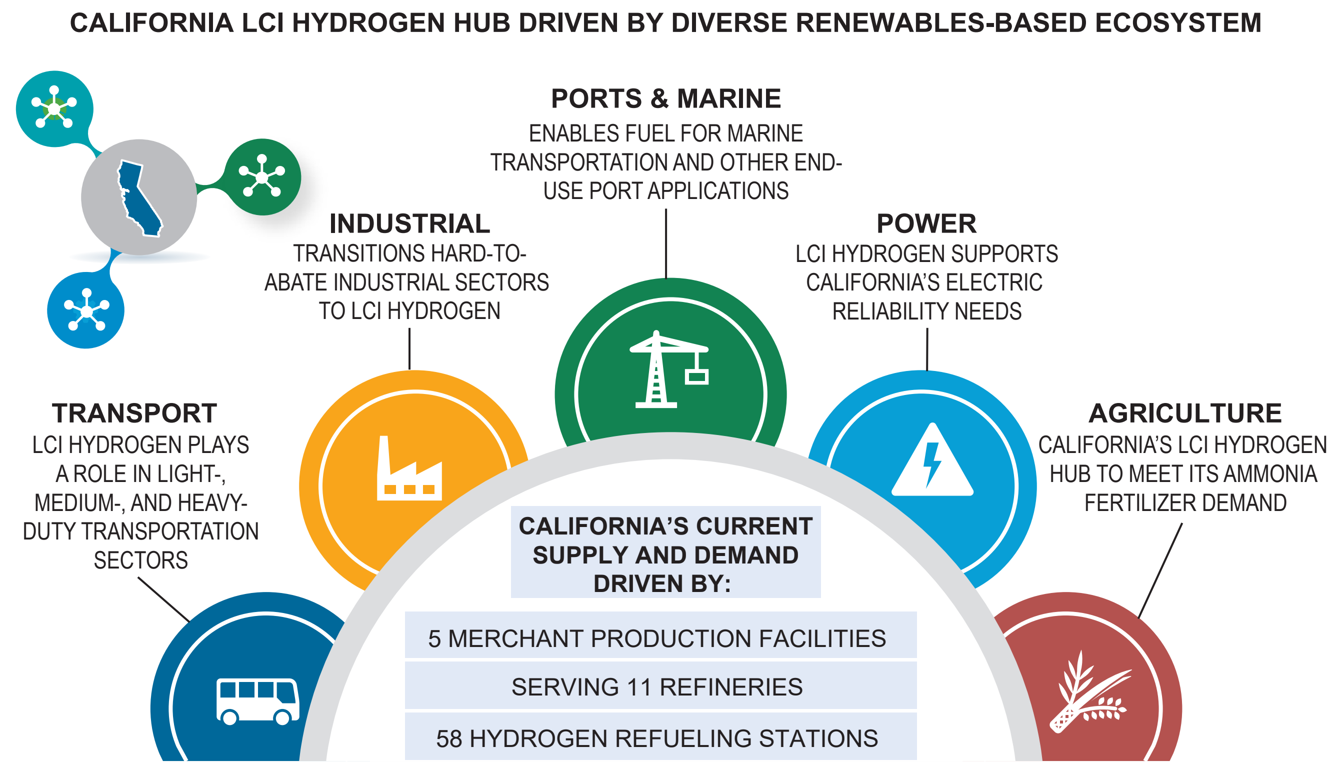


Figure 3-33. *California Region Sectoral Opportunities for LCI H_2 Hub Development*

the marine transport and shipping sector, California's major ports could use LCI H_2 to support demand as a fuel for marine transportation and other end-use port applications. California, as a major agricultural production region in the United States, has the potential to leverage its LCI H_2 hub to meet its ammonia fertilizer demand.

To support a geographically dispersed LCI H_2 supply and end-user needs in California, a variety of transport, storage, and delivery infrastructure solutions would be required. As part of LCI hub integration, hydrogen produced from geographically dispersed electrolytic hydrogen production facilities could be transported via LCI H_2 pipeline and storage network before being delivered to end users via trucks (either gaseous or liquid phase). LCI H_2 could contribute to California's commitment to combating climate change, reducing greenhouse gas emissions, and transitioning to a cleaner, more sustainable energy system. As part of this transition, California's development of an integrated LCI H_2 hub has the potential to make a strong contribution as the state continues to innovate and implement measures to accelerate the deployment of renewable energy technologies and drive the transition to a low-carbon future. Addressing infrastructure permitting challenges, supporting RD&D toward hub development programs, supporting demand-side incentives, and being inclusive of hub development as part of state's climate policy actions can help enable commercial interests in California.

IX. THE ROLE OF HYDROGEN EXPORT-IMPORT INFRASTRUCTURE

A. Introduction

Hydrogen export-import infrastructure is an important enabler of global LCI H_2 trade flows and may benefit exporting countries with economies of scale to promote a cost-competitive global hydrogen trade-flow market.

Assuming that global demand for LCI H_2 grows over the coming decades, the United States has the potential to become a large-scale exporter of hydrogen and hydrogen carriers. Where feasible, pipelines can be used to transport gaseous hydrogen between countries. Where shipping is required, hydrogen can be converted to ammonia, which is already shipped internationally. Emerging pathways for international transport include the shipping of liquid hydrogen and LOHC, which both face technological and economic barriers for large-scale use. This section outlines the potential role of hydrogen export/import infrastructure in supporting global trade flows across these various carrier pathways.

B. Gaseous Hydrogen Infrastructure

Where feasible, onshore and subsea pipeline infrastructure can be used to transport gaseous LCI H_2 between countries. For example, the European Hydrogen Backbone envisions five hydrogen pipeline corridors to connect EU countries with various sources of supply, including North Africa and the North Sea.[159] For the United States, potential export markets for gaseous hydrogen include Canada and Mexico, both of which could be supplied by onshore pipelines.

C. Ammonia Carrier Infrastructure

As described in Section IV.D of this chapter, transporting ammonia using ships is mature and well established in the United States and globally. Ammonia is produced on a large-scale, traded internationally (10% of global production), and is supported by existing infrastructure in more than 120 ports globally.[160] There are ammonia terminals at 38 ports that export ammonia and 88 ports that import ammonia, with six ports capable of both exporting and importing.[161] The majority of current ammonia trade is interregional, with the largest flows to neighboring regions rather than globally (Middle East to Asia, Latin America to North America, Eurasia to Europe).[162] At the import terminal, ammonia is unloaded from the carriers and stored in tanks or vessels. From there, the ammonia can subsequently be cracked to recover the hydrogen or used directly as fuel. The recovered hydrogen can be distributed to end users through various distribution transport options, including trucks and pipelines. To serve export demand for ammonia made from LCI H_2, the United States would need to add to, or expand, its existing ammonia infrastructure, including pipeline, storage, and ship loading facilities.

D. Liquid Hydrogen Carrier Infrastructure

Liquid hydrogen has a much higher density than gaseous hydrogen, making long-distance transportation by ship feasible. Liquid hydrogen also has an advantage over LOHC in that it only must be regasified on the receiving end, while LOHC must undergo a chemical conversion process to recover the hydrogen. However, there are significant technical challenges involved in scaling up the technologies for hydrogen liquefaction and shipping. For example, to reach a size comparable to current natural gas liquefaction plants, the average hydrogen liquefaction facility would need to be scaled up by a factor of more than 220.[163] Furthermore, as described in Section IV.B of this chapter, ship transport of liquid hydrogen is currently in its infancy. If the technologies for liquefaction and shipping of hydrogen can be scaled to the point that they are economically viable, then the United States would be well-positioned as a potential exporter of liquid hydrogen. This would likely require the construction of new liquefaction and ship loading facilities, although there might be some benefit in colocating these facilities with existing LNG export facilities.

E. LOHC Carrier Infrastructure

Like ammonia, LOHCs act as a carrier for hydrogen. As described in Section IV.D of this chapter, the benefit of LOHCs is that they can be handled the same as any other hydrocarbon that is a liquid at ambient conditions, allowing them to be transported and stored using existing infrastructure, including tanks, trucks, pipelines,

159 European Hydrogen Backbone. 2022. "Five Hydrogen Supply Corridors for Europe in 2030." https://ehb.eu/files/downloads/EHB-Supply-corridors-presentation-ExecSum.pdf.

160 European Hydrogen Backbone. 2022. "Five Hydrogen Supply Corridors for Europe in 2030." https://ehb.eu/files/downloads/EHB-Supply-corridors-presentation-ExecSum.pdf.

161 European Hydrogen Backbone. 2022. "Five Hydrogen Supply Corridors for Europe in 2030." https://ehb.eu/files/downloads/EHB-Supply-corridors-presentation-ExecSum.pdf.

162 European Hydrogen Backbone. 2022. "Five Hydrogen Supply Corridors for Europe in 2030." https://ehb.eu/files/downloads/EHB-Supply-corridors-presentation-ExecSum.pdf.

163 IRENA. 2022. "Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Technology Review of Hydrogen Carriers." https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Apr/IRENA_Global_Trade_Hydrogen_2022.pdf?rev=3d707c37462842ac89246f48add670ba.

PATHWAYS	PIPELINE – H_2 GAS	AMMONIA	LIQUID H_2	LOHC
PROS	• Proven technology • No conversion required	• Proven technology • Already traded globally • High energy density • Can be burned directly as fuel or used as fertilizer/feedstock	• No conversion needed • Low energy consumption for regasification	• Can be transported using existing infrastructure
CONS	• Only feasible where onshore or submarine pipelines can be constructed	• High energy consumption for ammonia synthesis and reconversion to hydrogen (if needed) • Toxic and corrosive	• High energy consumption for liquefaction • Boil-off losses during shipping • Liquefaction and shipping technologies require scale-up	• High energy cost for dehydrogenation • High cost for carrier compound replenish-ment

Figure 3-34. *Advantages and Disadvantages of Hydrogen Carriers*

railcars, and ships. LOHC must go through a reconversion (dehydrogenation) process at import terminals to release the hydrogen for use or further distribution. The main drawback to LOHC transport is economic, driven primarily by the energy expense for dehydrogenation, as well as the cost to replenish carrier degradation and losses. If LOHC technology can overcome these economic hurdles, then the United States is well-positioned to leverage its existing liquid hydrocarbon infrastructure to satisfy export demand for LOHC.

The advantages and disadvantages of the carriers on a relative basis are illustrated in Figure 3-34.

F. Ports as a Center for Hub Development

Ports with infrastructure to export and import LCI H_2 also have the potential to serve as infrastructure-based hydrogen hubs, where networks of LCI H_2 producers, potential hydrogen consumers, and connective infrastructure are in proximity. Many ports (e.g., the Port of Houston), already serve the hard-to-abate industries that could benefit from the use of LCI H_2 as a pathway to industrial decarbonization. This demand will provide a natural pull for LCI H_2 production from a range of processes. Finally, ports also serve as hubs for heavy-duty vehicle transport and therefore represent a prime target for use of LCI H_2 in the transport sector.

Based on the stated projects thus far, the IEA estimates that roughly 50 terminals and port facilities for the trading of hydrogen and ammonia might be completed by the end of the decade. Several ammonia import ports have been announced across Europe, mainly in the Netherlands, Belgium, and Germany. The Port of Rotterdam aspires to be an international hub for LCI H_2 production, import, application, and transit to other northwest European countries. OCI Global received FID in 2022 for the expansion of its existing ammonia terminal, and it is evaluating the viability of constructing a new storage tank in the Port of Rotterdam. Apart from relevant port infrastructure, various large-scale ammonia cracking projects have been announced, albeit the technology has yet to be commercially demonstrated. Facilities in Wilhelmshaven, Rostock, and Brunsbüttel (Germany), Antwerp (Belgium), Liverpool and Immigham (United Kingdom), and two facilities in Rotterdam (Netherlands) are being considered, which may crack ammonia to supply around 1.5 MT H_2 by 2030.[164] The lessons learned from the

164 IEA Global Hydrogen Review, 2023.

Port of Rotterdam could help drive comparable hub development in the United States.

X. RESEARCH GAPS AND ENABLERS FOR MARKET SCALE-UP

A. Introduction

Myriad challenges could stymie LCI infrastructure development and adoption at-scale. Identifying and bridging the key research gaps is key to enabling LCI H_2 infrastructure adoption at-scale.

Challenges remain in enabling the development and expansion of LCI H_2 infrastructure in the United States. The DOE's comprehensive 2021 survey (as part of the DOE hydrogen summit) identified several potential barriers, including a lack of sufficient hydrogen infrastructure, public awareness and understanding of hydrogen, the need for technological advancements, and the need to reduce the delivered cost of hydrogen to end users.[165]

The challenges in technology, policy, regulatory, safety, societal and environmental impacts, and end-use requirements can stymie the development of scalable and cost-effective LCI H_2 transportation, storage, and delivery infrastructure. This section of the chapter identifies key technological challenges (as illustrated in Figure 3-35) specific to infrastructure and addresses potential enablers to fill those gaps.

B. Addressing Research Gaps: Infrastructure Safety

Hydrogen has been used in various industries for decades and has a mature transportation, storage, and delivery infrastructure. A well-developed safety protocol exists today in infrastructure design, operations, and maintenance and covers hydrogen transport, storage, and delivery. As the demand for LCI H_2 is expected to grow to 75 MMTpa by 2050[166] under the NZ2050 scenario, additional infrastructure pathways and technologies (such as repurposing existing natural gas infrastructure, measurement, and monitoring of hydrogen emissions) would be needed to support the growth trajectory. There is a need to evaluate additional safety measures as the infrastructure evolves over time. Research needed to support the development of new technologies focused on

165 DOE. 2023. https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap.

166 Value as predicted by the 2023 MIT economic modeling effort sponsored by the NPC to support this report preparation.

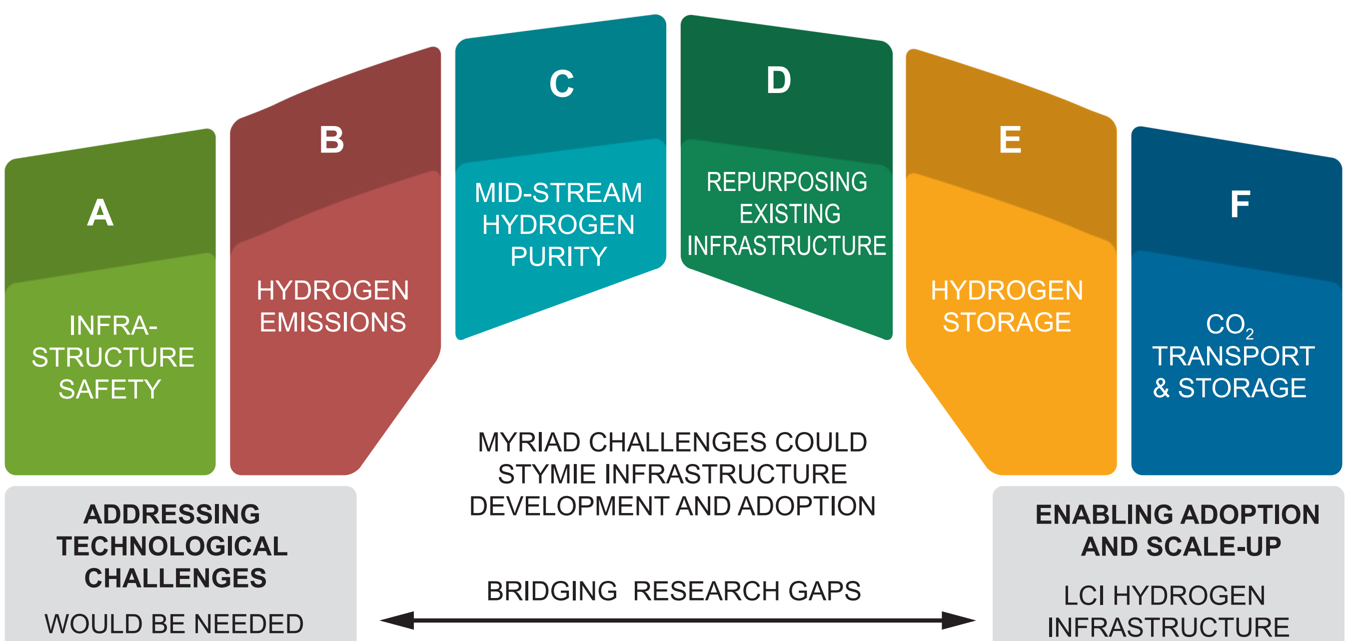


Figure 3-35. *Addressing Research Gaps Is Key to Enabling LCI Hydrogen Infrastructure Adoption At-Scale*

infrastructure safety will help address and mitigate potential safety and health-related risks. Developers, investors, and stakeholders require assurance that safety risks are identified, evaluated, and managed appropriately. By putting safety first, industry players can effectively manage risks, protect investments, and lay a solid foundation for the safe and reliable growth and sustainability of the LCI H_2 economy.

Evaluating the system and operational safety of existing hydrogen infrastructure as new emerging technologies are integrated and become commercialized and operational is critical for the development of a safe and functional LCI H_2 infrastructure. Hydrogen is a highly flammable and combustible gas and safety is a concern when working with it. Its unique molecular and combustible properties require safety systems to protect human life, prevent injuries, and avoid property damage from potential accidents, leaks, fires, or explosions. Robust and effective safety regulations, emergency response planning, and infrastructure integrity measures are required to ensure the safe handling, transportation, and storage of LCI H_2 in the envisioned diverse mix of infrastructure technologies. A lack of public awareness about and understanding of hydrogen as an energy carrier could lead to resistance to its adoption. Thus, education and communication programs are needed to raise public awareness and understanding of hydrogen's potential benefits, as well as the safety concerns.

Safety considerations are of paramount importance when blending LCI H_2 into the natural gas grid or repurposing infrastructure into dedicated hydrogen service. Further research is required to assess potential safety risks associated with both partial conversion through blending and full conversion. This includes leak detection, hydrogen embrittlement, equipment failure modes, explosion hazards, and operational safety protocols based on the material type, age, and condition of the existing natural gas infrastructure. Understanding all the research gaps and optimizing the natural gas infrastructure modifications will facilitate the safe and efficient blending of LCI H_2.

Leak detection and monitoring systems, ventilation and gas management technologies, flame and explosion mitigation technologies, pressure relief devices and safety valves, material testing and selection for hydrogen compatibility, hydrogen sensors and safety shut-off systems, fire suppression and extinguishing systems, and advanced hydrogen safety modeling and simulation tools are some of the key technological solutions that contribute to hydrogen infrastructure safety.

Addressing the safety challenges of LCI H_2 infrastructure requires a comprehensive approach that incorporates safety awareness and education into design, operation, and regulation of the overall system. To better understand the safety characteristics of individual LCI H_2 technologies that make up the overall infrastructure, the LCI H_2 industry, academic research institutions, governmental agencies, and U.S. national labs should prioritize investments in RD&D. This includes assessing LCI H_2 behavior, review of infrastructure integrity system design (material compatibility), understanding equipment failure modes, defining system risks via failure modes, and identifying (and mitigating) safety risks. Once these are understood, the stakeholders will perform hazard assessment tests, and develop advanced operational safety protocols, technologies, as well as materials to improve system integrity and operational safety of LCI H_2 transportation, storage, and delivery infrastructure. Conducting pilot demonstration projects in real-world settings to validate the safety of hydrogen technologies can provide valuable insights into safety performance, identify potential challenges, and demonstrate effective safety practices. Lessons learned from these initiatives can be used to improve safety standards and inform future LCI H_2 infrastructure development.

Collaboration among industry players, researchers, regulatory bodies, and other stakeholders is needed to share knowledge, experiences, and best safety practices. Knowledge-sharing platforms for information exchange, collaborative research, and lessons learned will accelerate safety advancements and facilitate the dissemination of safety-related information across the industry.

C. Addressing Research Gaps: Fugitive Emissions

Hydrogen is the smallest possible molecule and has lower density and viscosity compared to other molecules, presenting challenges for transportation, storage, and delivery. Hydrogen may permeate materials and has the potential to diffuse into sealing materials, causing damage. Minimizing leakage and releases from hydrogen-containing infrastructure is critical to ensuring safety and mitigating potential climate impacts. Emissions rates across the hydrogen value chain are still highly uncertain due to both limited measurements and measurement technology; both require continued study to accurately assess leak rates and to design infrastructure with minimum leakage.

Compared to other traditional sources of energy, hydrogen is more readily ignited and has a wider flammability range and a lower ignition energy than natural gas and gasoline. Fires can be larger, burn hotter, and be more difficult to detect.[167] Hydrogen tends to disperse quickly, but if there is leakage in enclosed spaces where hydrogen may accumulate, a safety incident could be severe.

As discussed in Chapter 1: Role of LCI Hydrogen, scientists have long known the indirect warming effects of hydrogen with several studies quantifying its impact.[168, 169, 170] Hydrogen emissions impacts will depend on how much is deployed to replace unabated hydrocarbon combustion and how much escapes to the atmosphere from the value chain. Hydrogen's potential warming effect (especially in the near term) means that any emissions (including leakage, venting, and purging) could start to offset the intended emissions reduction benefits of hydrogen deployment.

Initial research shows that high levels of leakage, for example, 1% or more, across the full global value chain could reduce the climate benefits of hydrogen with higher climatic impact in the near term. Recent studies suggest that every 1% of value chain hydrogen emissions would reduce the climate benefit by 1.2% to 4.2% in the near term (20 years) and 0.4% to 1.3% in the long term (100 years) (lower estimate from Warwick et al., 2023, upper estimate from Hauglustaine et al., 2022).[171,172] The net climate benefits of hydrogen usage would be further reduced by the carbon intensity of the production method, which is separately accounted for in the LCA pathways outlined in this study and considered in the modeled outcome scenarios (see Chapter 1: Role of LCI Hydrogen).

A previous study from the Environmental Defense Fund on the climate consequences from hydrogen emissions[173] reported that hydrogen emissions can undermine the GHG emissions reduction potential of LCI H_2 technologies and the associated infrastructure. Therefore, beyond quantifying the hydrogen leakage, advanced research focusing on the holistic understanding of global warming potential of hydrogen emissions is essential.[174] To fully understand the impacts of hydrogen emissions on the climate associated with hydrogen deployment, hydrogen emissions from real-world facilities must be quantified with empirical measurements. Whereas assessment of emissions rates by an operator with access to hydrogen facilities (production, storage, and end use) can be accomplished with less sensitive, albeit not-yet-commercially-available equipment, learnings from over a decade of research with methane emissions measurement suggest that hydrogen emissions quantification based on fence line measurements or for wide-area assessments (e.g., pipelines) would likely require hydrogen sensors that are fast (respond in a few seconds) and sensitive (with very high precision levels, see Chapter 1: Role of LCI Hydrogen).

167 DOE. 2019. "Safe Use of Hydrogen." https://www.energy.gov/eere/fuelcells/safe-use-hydrogen.

168 Paulot, F., Paynter, D., Naik, V., Malyshev, S., Menzel, R., and Horowitz, L.W. 2021. "Global Modeling of Hydrogen Using GFDL-AM4.1: Sensitivity of Soil Removal and Radiative Forcing." *International Journal of Hydrogen Energy.* 46 (24): 13446–60. https://doi.org/10.1016/j.ijhydene.2021.01.088.

169 Sand, M., Skeie, R.B., Sandstad, M., Krishnan, S., Myhre, G., Bryant, H., Derwent, R., et al., 2023. "A Multi-Model Assessment of the Global Warming Potential of Hydrogen." *Communications Earth & Environment.* 4 (1): 1–12. https://doi.org/10.1038/s43247-023-00857-8.

170 Warwick, N.J., Archibald, A.T., Griffiths, P.T., Keeble, J., O'Connor, F.M., Pyle, J.A., and Shine, K.P. 2023. "Atmospheric Composition and Climate Impacts of a Future Hydrogen Economy," March. *Atmospheric Chemistry & Physics.* https://doi.org/10.5194/acp-2023-29.

171 Warwick et al., 2023.

172 Hauglustaine, D., Paulot, F., Collins, W., Derwent, R., Sand, M., and Boucher, O. 2022. "Climate Benefit of a Future Hydrogen Economy." *Communications Earth & Environment.* 3 (1). https://doi.org/10.1038/s43247-022-00626-z.

173 Ocko, Ilissa B., and Steven P. Hamburg. 2022. "Climate Consequences of Hydrogen Emissions." *Atmospheric Chemistry & Physics.* 22 (14): 9349–68. https://doi.org/10.5194/acp-22-9349-2022.

174 Ocko et al., 2022.

1. Lessons Learned from Methane Infrastructure

Policies for managing leaks from natural gas (methane) infrastructure are a useful starting point when considering best practices for hydrogen. Historically, natural gas infrastructure leaks were managed and regulated solely with a focus on minimizing safety incidents—for example, natural gas leaks are graded on a safety-based scale (leaks prioritized for repair are those deemed hazardous to people and property), and transmission pipeline locations are classified based on their proximity to human populations.[175] As methane's potency as a greenhouse gas has become better understood,[176] governments and companies have begun to regulate and manage methane leakage and releases from an environmental perspective, and not only to ensure safety.[177, 178] This approach improves overall infrastructure management by prioritizing both safety and environmental outcomes, which are mutually reinforcing.

LCI H_2 infrastructure should be planned, built, and managed to reasonably minimize releases. These considerations are also applicable if existing methane infrastructure is being repurposed and converted to hydrogen service. Hydrogen leaked into the atmosphere as an indirect greenhouse gas also poses explosion risks, requiring both environmental and safety considerations as part of comprehensive leak detection and management strategies. Hence, the infrastructure planning processes must incorporate effective protocols and standards to minimize hydrogen releases across the entire value chain.

2. Blending Requires Special Consideration

Improved understanding of hydrogen leakage under various hydrogen blend percentages with natural gas is needed. Given the small molecular characteristics, hydrogen has the potential to diffuse through certain materials, leading to degradation of pipeline and storage tank materials over time. The age, condition, and material considerations of the infrastructure could also impact the likelihood of fugitive emissions. Analyses have found that hydrogen/methane blends with higher hydrogen percentages leak faster compared to methane alone.[179] When blending hydrogen with methane in existing natural gas infrastructure is considered, leakage impacts from a safety and environmental perspective should be comprehensively evaluated. Refer to Section VII.B of this chapter for detailed evaluation on the technical impacts of blending into existing natural gas infrastructure.

3. Improved Understanding of Hydrogen Leakage

Considering all the uncertainties, improved leak detection technology and documented measurements are needed to better understand hydrogen leak rates. Once understood, improved mitigation strategies can be developed. Table 3-4 illustrates the wide range of estimates of fugitive emissions from the hydrogen infrastructure value chain across several published studies.

Even though the emissions from compressed gas and liquefied hydrogen truck transportation are significantly higher, the amount of hydrogen transport through these mediums is significantly lower compared to pipeline transmission and distribution networks. Therefore, in addition to fractional emissions data, it is important to incorporate volume of transportation to assess the overall emissions.

Hydrogen emissions from real-world facilities must be quantified with empirical measurements, which will require highly sensitive hydrogen sensors and procedures that are not commercially available now.[180] Research support is needed for development of advanced hydrogen

175 See 49 C.F.R. § 192.5 (defining class locations in PHMSA pipeline regulations).

176 Environmental Defense Fund. 2018. "Methane Research Series: 16 Studies." https://www.edf.org/climate/methane-research-series-16-studies.

177 California Legislative Information. 2014. "Natural Gas: Leakage Abatement." https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201320140SB1371.

178 Massachusetts Legislature. 2014. "Uniform Natural Gas Leaks Classification System." https://malegislature.gov/Laws/GeneralLaws/PartI/TitleXXII/Chapter164/Section144.

179 Raju et al., 2022.

180 Rowan, S.L., Kim, D., Belarbi, Z., Wells, A.L., Hill, D.J., Dutta, B., Bayham, S., Bergen, R., and Chorpening, B. 2023. "Hydrogen Safety Review for Gas Turbines, SOFC, and High Temperature Hydrogen Production." OSTI OAI (U.S. Department of Energy Office of Scientific and Technical Information). https://doi.org/10.2172/1969531.

Hydrogen Infrastructure	Low Estimate (%)	High Estimate (%)
Transportation-Tube Trailer Trucks (Compressed Gas)	0.3	5.5
Transportation-Tube Trailer (Liquefied Hydrogen)	3.76	13.20
Conversion (Compression/Liquefaction)	0.14	2.21
Transportation-Transmission Pipelines	0.02	5
Transportation-Distribution Pipelines	0.0003	0.53
Storage Aboveground (Compressed Gas)	0.3	6.52
Storage-Salt Caverns (Compressed Gas)	0.02	0.06

Sources: Cooper et al., 2022, “H_2 Emissions from the Hydrogen Value chain-emissions profile and impact to global warming,” https://www.sciencedirect.com/science/article pii/S004896972201717X?via%3Dihub; Frazer Nash Consultancy, 2022, “Fugitive Hydrogen Emissions in a Future Hydrogen Economy,” https://www.gov.uk/government/publications/fugitive-hydrogen-emissions-in-a-future-hydrogen-economy; Van Ruijven et al., 2011, “Emission scenarios for a global H_2 economy and the consequences of global air pollution,” https://www.sciencedirect.com/science/article/pii/S0959378011000409; Arrigoni A. Bravo Diaz, JRC Technical Report, “Hydrogen emissions from a hydrogen economy and their potential global warming impact,” https://publications.jrc.ec.europa.eu/repository/handle/JRC130362.

Table 3-4. *Summary of Hydrogen Emissions Rates from Existing Literature Survey*

leakage prevention and monitoring technologies to help evaluate and accurately measure fugitive emissions, and to develop technologies to mitigate intentional hydrogen releases (boil-off). As these efforts proceed, development of leak survey and repair technologies, in addition to industry leading safety and environmental practices, will help minimize future releases from LCI H_2 infrastructure.

4. Considerations for Leak Management

Several factors may impact fugitive emissions of hydrogen and its impact:

- **Flame characteristics:** The wider flammability range of hydrogen (4% to 75%), when compared to methane (4.5% to 15%) has increased importance when evaluating hydrogen fugitive emissions, including when hydrogen is blended with natural gas.
- **Seal design:** Design parameters regarding seal compression and base materials for the seals should be considered. Seal materials can become embrittled and/or have voids trapped inside the material, which, when subjected to a rapid depressurization, could lead to seal failure. Other seal material, such as rubber O-rings, are subject to swelling.
- **Threaded connections:** Threaded connections are widely used for steel distribution piping, especially on meter assemblies, and a variety of thread sealants have been used. The sealants should provide sufficient strength and reliable sealing to avoid tampering, damage, and loosening. Threaded connections are leak sources with natural gas and the likelihood of leaks increases with hydrogen.
- **Odorants:** Currently there is no known odorant suitable for hydrogen and natural gas blends that was shown to travel with hydrogen at an equal dispersion rate.[181] The current odorants impact the effectiveness of some end users' (especially fuel cell) equipment and processes. Potential solutions include the research and development of an odorant-compatible, element/compound offering system compatibility with all end-use equipment/processes, including fuel cells, and to develop equipment to remove the unwanted compounds to preserve end-use equipment and processes.

DOE, along with the National Renewable Energy Laboratory and Sandia National Laboratory, are currently addressing several aspects to evaluate fugitive emissions from hydrogen, with concerted efforts to collect pertinent data on hydrogen leak rates, understand the leakage behavior of blended LCI H_2, and support the advancement of hydrogen sensors and leak detection technologies.[182] Additional research on LCI H_2 leakage, including research, development,

181 Pipeline Research Council International. 2020. “Emerging Fuels-RNG SOTA Gap Analysis and Future Project oadmap.” https://www.prci.org/Research/Measurement/MEASProjects/MEAS-15-03/178561/204297.aspx.

182 Topolski et al., 2022.

and demonstrations, can help test and evaluate different leak detection and prevention technologies, and thus help detect and prevent leaks more effectively. Pilot demonstration projects can be used to test and evaluate different safety measures, develop hydrogen emissions prevention standards, and test emergency response procedures and protocols, which can help to minimize the impact of leaks and accidents if they occur. The data collected from demonstration projects can inform the development of regulations and guidelines for hydrogen transportation, storage, and delivery infrastructure to ensure that hydrogen is handled, transported, and delivered safely.

D. Addressing Research Gaps: LCI Hydrogen Purity

LCI H_2 purity standards are an important consideration when transporting, storing, and delivering hydrogen to meet specific end-use requirements. As LCI H_2 is used in new sectors as part of the future clean energy transition, it is essential to evaluate and develop LCI H_2 purity standards to ensure the safety and reliability of end-user requirements. Improved understanding of hydrogen purity impacts will be needed when leveraging emerging and energy storage technologies.

The purity refers to the concentration of impurities (water vapor, oxygen, and other gases) in the LCI H_2. Maintaining purity as part of the LCI H_2 infrastructure value chain (including transportation, storage, and delivery systems) is critical for safety, equipment reliability, end-use application performance, environmental concerns, and quality control measures. Impurities in LCI H_2 may react with other substances, posing environmental and safety risks, such as leakage, corrosion, material embrittlement, or combustion-related risks. The development of robust purity standards across the LCI H_2 infrastructure could help address the above risks. The following standards and guidelines should be followed to ensure that LCI H_2 meets end-use requirements:

- **Purity specifications:** LCI H_2 purity standards should be established and clearly defined, specifying the maximum allowable concentrations of impurities such as water vapor, oxygen, and other gases. These standards may vary depending on the end-use application requirements and should be regularly measured and monitored across the LCI H_2 infrastructure value chain to ensure purity compliance.
- **Transportation, storage, and delivery methods:** LCI H_2 transportation, storage, and delivery pathways can have an impact on the purity of LCI H_2 due to potential opportunities for impurities to be introduced, depending on the type of transport and storage method (see Section IV of this chapter describing the potential pathways to transport, store and deliver LCI H_2).
- **Drying and purification methods:** The presence of water vapor, which can be absorbed by hydrogen during production, transport, and storage, can affect the purity of LCI H_2. To meet the end-use purity requirements, drying and purification methods will be needed to remove water vapor and other impurities. Hydrogen purification and drying equipment may increase the cost and complexity of the infrastructure, particularly when injecting and transporting hydrogen over long distances, and these challenges must be carefully evaluated and balanced with the benefits and safety of the LCI H_2 infrastructure system.
- **Quality control and traceability:** Robust procedures should be established to ensure that the required purity standards of LCI H_2 are maintained throughout the entire transportation, storage, and delivery process, as well as establishing quality control and traceability mechanisms to monitor hydrogen quality from production to end user.
- **Varying end-user requirements:** The impact of impurities varies depending on the end-user applications and the nature of the impurity in the system. The international organization for standardization (ISO 14687:2019)[183] specifies the minimum hydrogen quality characteristics for hydrogen for end-user applications, including fuel cells in vehicular transport and stationary applications. The minimum LCI H_2 purity standard for fuel cell vehicles is greater than 99.9%, with impurities (water vapor, oxygen,

183 International Organization for Standardization. November 2019. "ISO 14687:2019: Hydrogen fuel quality-Product specification." https://www.iso.org/standard/69539.html#:~:text=ISO%20 14687%3A2019%20Hydrogen%20fuel%20quality%20%

and other gases) kept at extremely low levels to prevent damage to the fuel cell and ensure optimal performance. LCI H_2 purity standards for industrial uses may vary depending on the specific application. For example, LCI H_2 used for chemical production could have lower purity requirements than LCI H_2 used for semiconductor manufacturing, where purity requirements can be quite high. For heating purposes, hydrogen purity, depending on the application, could range between 98% and 100% as in the U.K. hydrogen quality standards for heat applications.[184]

Minimum hydrogen purity standards may be determined by technical considerations, safety, and end-use application performance requirements, and they may evolve as the LCI H_2 system infrastructure and technology mature in the future.

It is essential to gain a thorough understanding of LCI H_2 purity levels needed to support a safe and dependable at-scale hydrogen economy by 2050. LCI H_2 purity standards, including monitoring and compliance mechanisms, would be needed to transport, store, and deliver to various end uses. Collaboration among industry players, researchers, regulatory bodies, and other stakeholders to share knowledge, experiences, and best practices regarding the purity of LCI H_2 would help enable the development of optimal purity levels required for transporting, storing, and delivering hydrogen to meet the specific end-use purity needs.

Government agencies and regulatory bodies could play a significant role in setting standards and regulations for LCI H_2 purity. These organizations will need to consider many factors (such as safety, environmental impact, and public health impacts, etc.) when establishing purity. They could collaborate with industry experts, stakeholders, and international bodies to develop comprehensive regulations.

E. Addressing Research Gaps: Blending and Repurposing

As emphasized in Section VII of this chapter, evaluating technical feasibility, end-use demand, and environmental and community impacts of converting existing natural gas infrastructure is essential before making decisions dictating which part of the existing system is viable for LCI H_2 conversion. Repurposing existing infrastructure has several research gaps that need to be addressed. Some of the key research gaps are identified in the following:

1. LCI Hydrogen Blending

There are several technical impacts needing additional research related to blending of LCI H_2 in the existing natural gas infrastructure (see Section VII.B.1 of this chapter).

Blending limits and optimization: Additional research would be needed to determine the allowable LCI H_2 blending levels in the natural gas grid without compromising safety, metallurgical and infrastructure integrity baseline, and end-use equipment performance. This involves understanding the impacts of LCI H_2 on gas quality, combustion characteristics, and material compatibility aspects. Optimizing the blending ratios is crucial to strike a balance between maximizing LCI hydrogen integration and minimizing safety and other potential issues, including fugitive emissions.

Previous studies have claimed hydrogen blending rates of up to 20% by volume without a need for modification in the existing natural gas pipeline network and end-user applications.[185] However, there is no established LCI H_2 blend percentage that can be safely blended in an existing natural gas pipeline infrastructure. The blending of LCI H_2 at any concentration into the natural gas network will require actions to evaluate and mitigate the technological, metallurgical, operational, and safety impacts to pipelines, compressor stations, and meters/regulators/valves, etc. Blending hydrogen into the natural gas infrastructure may require certain modifications or upgrades to pipelines, compressors, and other infrastructure components.

LCI H_2 blending could have significant impacts on the metallurgical integrity of the existing

184 Hy4Heat. 2019. "Hydrogen Purity." https://static1.squarespace.com/static/5b8eae345cfd799896a803f4/t/5e58ebfc9df53f4eb31f7cf8/1582885917781/WP2+Report+final.pdf.

185 Lipiäinen, S., Lipiäinen, K., Ahola, A., and Vakkilainen, E. 2023. "Use of Existing Gas Infrastructure in European Hydrogen Economy." *International Journal of Hydrogen Energy*. 48 (80): 31317–29. https://doi.org/10.1016/j.ijhydene.2023.04.283.

natural gas infrastructure. With blending, all grades and vintages of natural gas pipe are susceptible to increased fatigue crack growth and reduced fracture toughness. Operating pressure variation has a significant impact on pipeline fatigue crack growth rates. Further research is needed to evaluate the metallurgical and infrastructure feasibility, failure modes, cost effectiveness of blended infrastructure, and operational readiness of the system. Collating research and experimental data will assist in evaluating the key factors in defining a robust operation, maintenance, and inspection program to support an efficient LCI H_2 blended infrastructure. This includes:

- Understanding the increase in the number of defects and unacceptable defects requiring complete dig and repair as a function of LCI H_2 blend percentage.
- Refining defect acceptability criteria as a function of LCI blend percentage.
- Understanding how operators should adjust (shorten) inspection intervals.
- Understanding how changes to inspection and maintenance programs will differ for LCI H_2 blending into natural gas distribution systems versus transmission and storage systems.
- Hot tapping or other operating procedures for working on or around lines should be developed, tested, and common issues assessed for impact of LCI H_2 blends.
- Understanding if pipeline cleaning and pigging requirements must change due to byproducts from the interaction of LCI H_2 and other components or contaminants.
- Developing, testing, and gathering data on new nondestructive testing tools for the detection of cracks, accelerated fatigue growth, and reduced flaw size in LCI pipeline and associated support infrastructure.
- Laboratory, demonstrations, or real-world pilot scale projects to assess the integrity of repair sleeves, composite wrap repairs, and rehabilitation methods under varying levels of LCI H_2 blending.
- Experimental research on understanding the effect of LCI H_2 blends on fatigue behavior of repaired pipe for various repair technologies.

Combustion and heat transfer: LCI H_2 has different combustion characteristics compared to natural gas, including higher flame speed, wider flammability range, and different heat release properties. Further research is needed to understand the impact of hydrogen blending on combustion dynamics, heat transfer rates, and burner performance. A thorough understanding of the combustion and heat transfer properties will help optimize end-user combustion systems and ensure reliable and efficient energy conversion.

End-use equipment compatibility: The compatibility of end-use equipment (boilers, furnaces, and appliances) with LCI H_2-blended natural gas is a critical area. Research is needed to assess the impact of hydrogen on the performance potential for fugitive emissions, potential health impacts from NO_x emissions, and durability of the end-user appliances, and to develop safety standards. Further research is needed to identify any necessary infrastructure modifications, retrofitting requirements, or replacement strategies to enable seamless and safe operation with hydrogen-blended gas.

Gas quality and measurement: Research is required to establish robust standards and measurement techniques for hydrogen-blended natural gas. LCI H_2 has different physical properties compared to natural gas (as discussed in Section VII.B.1 of this chapter) and can affect the accuracy of traditional natural gas meters when measuring hydrogen-blended gas. Work is needed to develop and validate measurement technologies and metering systems that can accurately account for the presence of hydrogen in the gas stream (and in varying amounts). Monitoring the gas composition (including the hydrogen content, impurity levels, and moisture content) is crucial for maintaining accurate billing and ensuring compliance with blending regulations. Standardization of gas-quality parameters will ensure consistent and reliable blending practices across the natural gas infrastructure.

2. Hydrogen Deblending

As discussed above, the existing natural gas infrastructure enables hydrogen transport as a blend of hydrogen and natural gas. Depending upon the varying end-use needs of hydrogen at the point of receipt, the blended hydrogen is separated (deblended) from natural gas with a specified purity. A study conducted by the Gas Transmission Network Innovation Allowance (GTNIA) in the United Kingdom established that hydrogen deblending can assist the transition to a low-carbon hydrogen transmission and distribution system.[186] Therefore, hydrogen deblending processes can be essential for deployment of the hydrogen blending value chain. There are well-established hydrogen separation processes (such as the pressure swing adsorption, membrane separation, and cryogenic separation processes). However, these technologies were not developed in the context of deblending hydrogen at the point of receipt as a blended fuel. Furthermore, since the hydrogen blending ratios may vary across the pipeline networks, the existing hydrogen separation technologies may not be optimal or readily implemented. Recently, a few technologies were investigated for hydrogen deblending processes. An electrochemical hydrogen pump was suggested for hydrogen deblending at HRS.[187] A proof of concept study conducted by GTNIA suggested that an optimized process consisting of cryogenic separation and a combination of pressure swing adsorption and membrane separation systems could be a viable option for hydrogen deblending. In 2022, Linde commissioned a hydrogen deblending demonstration plant in Germany capable of producing high-purity hydrogen across varying blend rates.[188] Currently, the economics of hydrogen deblending leveraging the existing technology maturity is not attractive. To further increase the technology readiness level of hydrogen deblending technologies, more RD&D efforts, especially demonstrating the deblending technologies in real-world applications at-scale, would be essential.

3. Full Conversion–Dedicated LCI Hydrogen Infrastructure

Fully converting existing natural gas infrastructure to transport and distribute LCI H_2 is an area of active research and development. While there has been progress in this field, there are still several research gaps that need to be addressed.

Compatibility and materials: One of the primary research gaps is understanding the compatibility of existing natural gas infrastructure with hydrogen. Hydrogen can cause embrittlement in certain steel materials and structural integrity issues. All grades and vintages of pipe are susceptible to increased fatigue crack growth and reduced fracture toughness. Operating pressure variation has a significant impact on fatigue crack growth rates. Pressure cycling must be evaluated and managed for pipelines to safely transport LCI H_2 as part of full conversion. Additional research might be needed to identify suitable materials and coatings that can withstand the transport and distribution of LCI H_2 over the long term.

Infrastructure modifications: Full conversion of natural gas infrastructure for LCI H_2 may require modifications to pipelines, compressors, and other components (regulating stations, metering, and valves). Research involving the assessment of degree of modification of existing infrastructure is needed to optimize these modifications, considering pressure requirements, flow rates, and potential retrofitting challenges.

Scale-up and cost: Scale-up studies are required to assess the scalability of repurposing natural gas infrastructure for hydrogen and its future implications to the natural gas system. This includes evaluating the economic viability of retrofitting existing infrastructure, identifying cost-effective solutions for large-scale LCI H_2 transportation using the existing natural gas system, evaluating stranded natural gas infrastructure through conversion, exploring implications of the reliability and resiliency of the natural gas system, and exploring potential funding mechanisms for the necessary infrastructure upgrades.

F. Addressing Research Gaps: Hydrogen Storage

As discussed in Section III of this chapter, a large-scale LCI H_2 economy will require ample and dependable storage. There are numerous hydrogen technologies and pathways available to meet variable demand needs, ranging from

186 Energy Networks Association. 2020. "Hydrogen Deblending in the GB Gas Network. https://smarter.energynetworks.org/projects/nia_nggt0156.

187 Jackson, C., Smith, G., and Kucernak, A.R. 2024. "Deblending and Purification of Hydrogen from Natural Gas Mixtures Using the Electrochemical Hydrogen Pump." *International Journal of Hydrogen Energy*. 52 (January): 816–26. https://doi.org/10.1016/j.ijhydene.2023.05.065.

188 IEA Global Hydrogen Review, 2022.

small-scale, distributed hydrogen storage for daily or weekly demand to seasonal storage for several weeks to months. To store hydrogen efficiently it must be compressed, liquefied, or converted into chemical compounds.

Developing underground geologic storage infrastructure, such as salt caverns, rock caverns, or depleted oil, saline aquifers, and gas reservoirs, is a promising path for large-scale LCI H_2 storage. The technology readiness level (TRL) (see Section X.H.2 of this chapter for additional information) of underground hydrogen storage (UHS) varies depending on the type of cavern formation. While the salt cavern is a matured geologic storage option (TRL of 8–9), technologies to leverage the geological structures in porous rock formations is are still nascent (TRL 3–4).[189] Numerous barriers related to geological, technical, safety, efficiency, and regulatory aspects need to be addressed. As discussed in Section IV.A of this chapter, the SHASTA initiative intends to assess the feasibility of storing hydrogen or hydrogen-natural gas blends in subsurface environments.[190]

To evaluate hydrogen storage across multiple storage pathways as discussed in Section IV.F of this chapter, additional research is needed to better understand the subsurface geochemistry behaviors and long-term metallurgical and storage infrastructure integrity of underground geologic pathways. More research is needed to examine the effects of LCI H_2 injection and withdrawal on the stability of these underground structures, wellbore integrity, storage purity, and the possibility of fugitive emissions, depending on the type of geological storage.

Geochemical reactions can cause loss of hydrogen due to dissolution into brine, reduction of pyrite to pyrrhotite, and interaction between calcite, hydrogen, and bacteria. More research is needed to understand the geochemical interactions between hydrogen, rock minerals, and brine. Since underground storage involves significant storage time, thermodynamics and kinetic geochemical modeling supported by the experimental data are required for a holistic understanding on the effect of geochemical reactions on the hydrogen storage.

Underground salt cavern storage is a commercially mature and proven method of storing large quantities of LCI H_2. However, solution mining new salt caverns generates significant amounts of brine from the development of salt caverns (8 m^3 of brine per 1 m^3 of cavity),[191] which may pose disposal or utilization challenges on-site. To ensure the safety and integrity of the caverns, the solution mining process requires careful engineering and monitoring. Environmental considerations are also important, as brine extraction and disposal can have negative effects on the environment if not properly managed. Water utilization and management are critical components of solution mining. Environmental considerations and long-term water management practices are critical to ensuring the responsible and efficient use of water resources throughout the process.

Storage of blended LCI H_2, even at low partial pressures, in existing geologic storage fields or depleted oil and gas reservoirs will require careful engineering evaluations to avoid any potential issues related to the storage facility's integrity, operation, efficiency, and safety. LCI H_2 can mix with residual natural gas, react with geologic subsurface structures, or undergo methanogenesis, all of which have an impact on the purity of LCI H_2. Blended LCI H_2 at any concentration will require actions to mitigate the effects of impurities in storage field wells, piping and associated meters, regulators, valves, and gas treatment facilities. The risk of hydrogen sulfide (H_2S) formation, microbial activity, and fugitive emissions from leaks must also be considered.

When designing new geologic hydrogen storage wells or converting existing geologic storage facilities to store LCI H_2, material performance is an important factor to consider. Long-term exposure to high pressures changes material performance, which can have an impact on the material integrity of the storage facility, as well

189 Tarkowski, R., and B. Uliasz-Misiak. 2022. "Towards Underground Hydrogen Storage: A Review of Barriers." *Renewable and Sustainable Energy Reviews* 162 (C). https://ideas.repec.org/a/eee/rensus/v162y2022ics1364032122003574.html.

190 IEA Global Hydrogen Review, 2022.

191 Trevor Lechter, ed., 2022. "Storing Energy, 2nd Edition." Elsevier. https://shop.elsevier.com/books/storing-energy/letcher/978-0-12-824510-1. ISBN: 9780128245118.

as reduce the capacity of downhole and wellhead equipment to withstand operating loads or maintain leak-tight seals, resulting in pressure containment loss in a storage well. Material selection must consider the possibility of H_2S exposure due to microbial response to LCI H_2 in the subsurface environment. H_2S can cause equipment and material degradation via stress corrosion cracking and synergistic damage caused by the combined effects of thermo-mechanical loading and environmental exposure. Microbial reactions to LCI H_2 can cause fractional hydrogen loss as well. Geological formations contain several hydrogen consuming microorganisms whose activity can lead to hydrogen loss, formation of H_2S, methane, loss of porosity, corrosion, etc., with undesirable outcomes affecting the efficiency of the UHS.[192] There is scant data on the influence of microbial response to geologic storage facilities and the effectiveness of mitigation techniques. As a result, extensive research is required to address potential negative impacts, the feasibility of converting existing natural gas reservoirs or depleted oil and gas reservoirs to store blended LCI H_2, as well as to understand the risks associated with the storage resources' safety, environmental impacts, compliance, and reliability.

While storing LCI H_2 as an LOHC (described in Section IV.B.1 of this chapter) provides the advantage of high energy density and ease of use, there are several challenges and research gaps that must be addressed before they can be widely used. These include developing catalysts to support efficient hydrogenation and dehydrogenation kinetics and further optimizing LCI H_2 synthesizing parameters to achieve faster reaction rates, minimize energy requirements, and improve the overall performance of LOHC energy storage systems. For LOHC systems to be widely adopted, they must be integrated into existing LCI H_2 infrastructure. Additional research may be required to ensure compatibility with existing storage, transportation, and utilization systems, such as adapting infrastructure—including pipelines and storage tanks—to handle LOHCs conversion and reconversion seamlessly. To realize the full potential of LOHC-based LCI H_2 storage, more research, technological advancements, and collaboration between academia, industry, and policymakers is required.

While metal hydrides have high LCI H_2 storage densities and the potential for reversible hydrogenation, there are several challenges and research gaps that must be addressed before they can be used effectively. To practically store hydrogen using metal hydrides, the kinetics of LCI H_2 absorption and desorption in metal hydrides are critical. Improved hydrogenation and dehydrogenation kinetics may be required, including the development of catalysts and processes that allow for fast and reversible reactions at moderate temperatures and pressures. To improve hydrogen storage performance and cycling stability, more research into the thermodynamic properties of various metal hydride systems may be required. Metal hydrides can store a significant amount of hydrogen, but more research is needed to improve their storage capacities. This includes investigating new metal hydride compositions, nanostructuring techniques, and alloying strategies to improve hydrogen storage capacity and material properties. Further research focused on increasing the reversibility of hydrogen absorption and desorption reactions, as well as understanding and mitigating degradation mechanisms that can limit cycling stability and capacity retention over repeated cycles is needed. Metal hydride composition, grain size, morphology, and surface properties must be controlled to optimize their hydrogen storage properties and overall performance. When addressing research gaps, it is critical to understand and mitigate potential safety risks such as heat generation, pressure buildup, and potential reactions with air or moisture to ensure safe handling, storage, and transport of hydrogen stored in metal hydrides.

G. Addressing Research Gaps: Carbon Dioxide Transportation and Storage

While significant progress has been made in carbon capture, transport, and storage technologies,[193] research is needed to help reduce costs and enhance operational efficiencies of carbon storage projects. Addressing these research

192 Tarkowski and Uliasz-Misiak. 2022.

193 DOE. 2020. "Carbon Capture, Utilization, and Storage R&D Programs." https://www.energy.gov/fecm/articles/carbon-capture-utilization-and-storage-rd-program-fact-sheet.

gaps will help overcome technical, economic, and social challenges associated with carbon transport and storage deployment at-scale.

Focusing on research to advance the development and enhancement of carbon capture technologies that can efficiently and economically capture CO_2 emissions from point sources (industrial processes, power generation, etc.), as well as directly from the air would be needed. Research is needed to advance the development and deployment of novel materials and processes for carbon capture that offer higher efficiency, lower energy requirements, and reduced costs. Exploration of advanced sorbents, such as MOFs and porous materials, and innovative capture technologies like membrane-based systems, enzyme-based capture, and electrochemical capture could improve the efficiency and effectiveness of the carbon capture systems. Research advancements in DAC can potentially offer a solution for capturing CO_2 emissions from dispersed sources and from sectors that are challenging to decarbonize.

Research areas to advance the investigation of CO_2 pipeline transportation by optimizing compression and injection processes, assessment of CO_2 impacts on pipeline integrity, and exploration of alternative transportation methods (trucking, rail, shipping) for regions without pipeline networks in the United States are needed.

To advance the development of carbon transport and storage technologies, efficiency gains can be made with new techniques for investigating the behavior of injected CO_2 in different reservoir types, assessing the integrity of storage sites, and developing monitoring techniques to detect and mitigate any potential leakage risks. Exploring alternative carbon storage options through conversion, such as mineralization and direct utilization, should also be considered. RD&D efforts to evaluate alternative storage formations such as basalt, depleted oil and gas reservoirs, and saline aquifers are needed. Additionally, studying CO_2 injection and storage under challenging conditions, such as deep-sea storage, might enable offshore CO_2 storage opportunities. Improved understanding of these storage options can expand the geographical availability and viability of carbon management solutions.

H. Market Enablers to Bridge the Research Gaps

Several market enablers are required to close research gaps and overcome potential barriers to the development of LCI H_2 technologies. These enablers contribute to the creation of a favorable environment for LCI H_2 technology research, development, and commercialization. Key market enablers as illustrated in Figure 3-36 can help to build an ecosystem that fosters the development and commercialization of emerging LCI H_2 transportation, storage, and delivery technologies, propelling the transition to an LCI H_2-based economy, and facilitating the widespread adoption of sustainable and low-carbon energy solutions.

1. Investing in RD&D to Advance LCI Hydrogen Infrastructure

Research investments are critical to the innovation and eventual commercialization of emerging transportation, storage, and delivery pathways, providing the funding and resources needed to advance research and development of new production, transportation, storage, and delivery technologies. Closing research gaps and developing new technologies will support the needed robust infrastructure development.

RD&D efforts help to overcome technical barriers, optimize processes, and unlock the full potential of LCI H_2 as an energy carrier through continuous research and innovation. Strategic investments in research and development help to reduce costs by enabling research into new materials, manufacturing processes, and system design. The cost of emerging technologies decreases as technology advances, economies of scale are achieved, and production processes become more efficient. RD&D investments also help to scale up the demonstration and deployment of emerging transportation, storage, and delivery technologies. They help build confidence among investors, policymakers, and end users by demonstrating the viability and effectiveness of these technologies in real-world applications. Successful demonstrations serve as proof of concept, stimulate market demand, attract private investment, and promote the development of a robust LCI H_2 infrastructure.

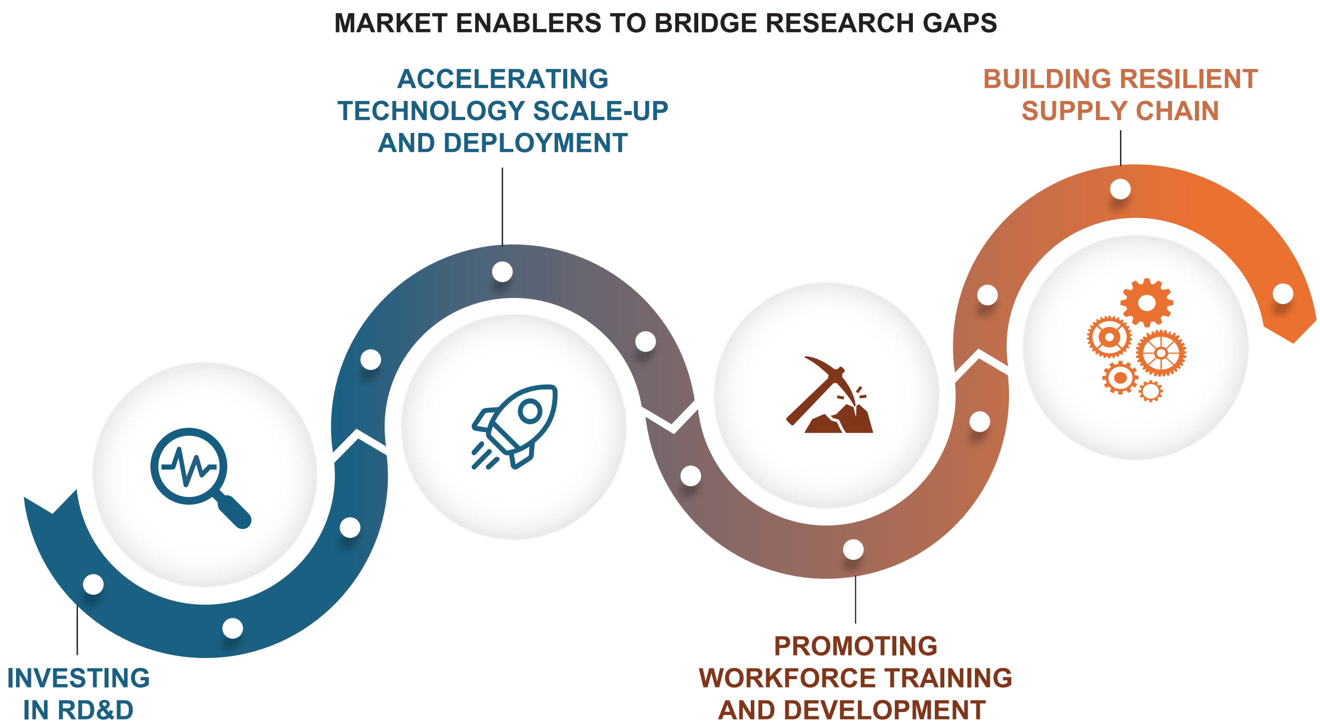


Figure 3-36. *Market Enablers Essential to Creating a Favorable Environment for LCI Hydrogen Technology Research, Development, Demonstration, and Deployment*

RD&D investments can influence policy decisions and create regulatory frameworks that are supportive of emerging technologies. These investments provide policymakers with evidence-based arguments to develop favorable policies, such as research grants, tax incentives, and supportive regulations, by demonstrating potential benefits and addressing technical challenges. Such policies can contribute to the creation of a favorable market environment, encourage private sector participation, and accelerate the growth and adoption of innovative transportation, storage, and delivery technologies. Investments in RD&D also promote international collaboration and knowledge sharing. Countries can pool their resources, avoid duplication of efforts, and accelerate the development of emerging pathways by participating in joint research initiatives, sharing data, and collaborating on projects. International collaboration also allows for the harmonization of standards, the exchange of best practices, and the development of a global hydrogen market.

RD&D investments are critical for propelling the growth of emerging hydrogen infrastructure-related technologies by advancing research, lowering costs, demonstrating viability, fostering knowledge development, influencing policies, and promoting international collaboration. These investments lay the groundwork for hydrogen's successful commercialization and widespread adoption as a clean and sustainable energy solution. Priorities for RD&D may shift as technologies mature and new challenges emerge. Interdisciplinary collaboration, knowledge sharing, and international cooperation are critical for the effective development and deployment of emerging LCI H_2 transportation and storage technologies that support environmental, economic, and societal benefits.

2. Technology Scale-Up and Deployment

Accelerating key LCI H_2 technologies that are driving transportation, storage, and delivery pathways through the TRL from RD&D to final commercialization requires a systematic and a strategic approach to support the progression of hydrogen technologies through the TRL stages.

Research and development (TRL 1–3): Investing in fundamental research to explore new concepts, materials, and processes that have the potential to advance certain technologies toward proof of concept and laboratory testing is essential. Fostering collaboration between research institutions, industry, and government agencies to leverage expertise and resources will be critical. Establishing research programs and funding mechanisms that support early-stage research and development activities and encourage knowledge sharing and dissemination of research findings through publications, conferences, and collaborations will be essential during this phase of development.

Proof of concept and laboratory testing (TRL 4–5): Translating promising research outcomes into practical demonstrations and laboratory-scale testing and developing prototypes or pilot systems to validate the feasibility and performance will be needed during this phase. Seeking funding and support from government agencies, industry partners, and venture capitalists to bridge the gap between research and development will bring in the needed support to help accelerate the advancement of select technologies toward demonstration.

Demonstration projects (TRL 6–7): Implementing demonstration projects at-scale to showcase the real-world application and performance of emerging technologies will be critical. Continuing to collaborate with industry partners, government agencies, and communities, and creating strategic partnerships for project implementation, will be an essential driver for the successful demonstration of key LCI H_2 technologies. The demonstration projects should focus on vital technology components, such as LCI H_2 production, transportation, storage, and delivery, to validate their functionality, efficiency, and reliability of the overall ecosystem in comparison to the incumbent technologies. Prudent data collection, performance monitoring, and documenting lessons learned to help refine technology designs and address any technical or operational challenges will enable key LCI H_2 technologies to be ready for scale-up and commercialization.

Scaling-up and commercialization (TRL 8–9): Scaling up successful demonstration projects to larger systems or facilities to ensure scalability and commercial viability and collaborating with industry partners to optimize technology designs, reduce costs, and increase production volumes will set the foundation for commercialization of technologies. It is important to seek the needed regulatory approvals and certifications to comply with safety and environmental standards. Successful commercialization models should include developing business models, market strategies, and partnerships to enable the commercialization of advanced hydrogen transportation, storage and delivery technologies, and engaging with investors, financial institutions, and government agencies to secure funding and support for commercial deployment.

During the Activation phase, policy and market support will require advocating for supportive policies, regulations, and market incentives that encourage technology adoption. Collaboration with government agencies to establish favorable market conditions, (e.g., targets, mandates, and financial incentives for technology deployment) will be critical for scaling. Engagement with industry associations, advocacy groups, and public representatives will be needed to build support for technology adoption during scale-up and commercialization.

Industry, academia, and government each play a crucial role in accelerating key hydrogen technologies through the TRL ladder from research to demonstration and final commercialization. Government agencies can provide RD&D funding support through grants, incentives, and financial programs to accelerate LCI H_2 technology development. Academia can collaborate with industry and government agencies to translate research findings into practical applications. Industry (through implementation of real-world projects) can validate technology performance, address operational challenges, and demonstrate economic feasibility, the essential first steps before moving to scale-up, demonstration, and commercial deployment. The collective contributions and shared results will support continued investments in manufacturing facilities, optimization of production processes, and leveraging economies of scale to reduce costs and improve U.S. competitiveness.

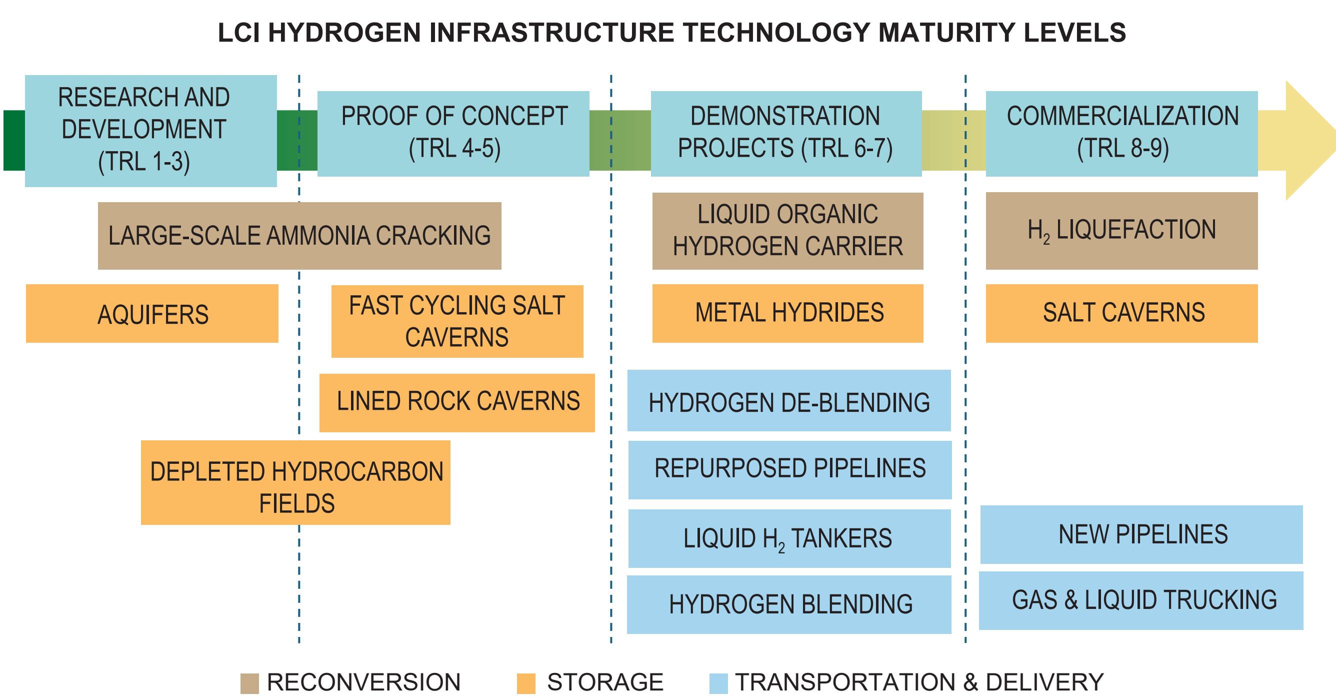
Figure 3-37 demonstrates the levels of technological maturity in LCI H_2 infrastructure throughout the various TRL categories mentioned above. Concentrating RD&D spending on promising technologies at each TRL level will provide the technology with the required support to get it closer to commercialization. However, because RD&D investment resources are limited, technologies must be prioritized. In the immediate term, repurposing existing natural gas infrastructure for hydrogen transportation and fugitive emissions from hydrogen infrastructure are the primary issues that require significant RD&D effort.

3. Workforce Training to Support Advanced Technologies

RD&D investments promote knowledge and skills development within the scientific and engineering communities. They support education and training programs, collaborative research projects, and the exchange of expertise. This helps to cultivate a skilled workforce and foster innovation in the field of LCI H_2 technologies, and strengthens the collaboration between academia, industry, and government. Advanced LCI H_2 technologies are expected to involve complex systems that require integration with existing infrastructure (or other renewable energy sources). Workforce training helps professionals understand the intricacies of system integration, operation, and optimization, ensuring efficient and seamless integration within the broader energy landscape. Workforce training programs provide opportunities for professionals to collaborate, share experiences, and learn from each other. This exchange of knowledge and best practices fosters a supportive network within the hydrogen industry, accelerating the collective learning and advancement of hydrogen technologies.

4. Robust Supply Chain to Advance, Commercialize, and Scale New Technologies

Supply chain plays a crucial role in commercializing advanced and emerging technologies by ensuring the reliable and efficient supply chains needed to advance new technological research. As the demand for LCI H_2 technologies increases, a well-optimized supply chain can leverage bulk



Sources: IEA, https://www.iea.org/reports/hydrogen-supply; *IEA Global Hydrogen Review,* 2023, https://www.iea.org/reports/global-hydrogen-review-2023.

Figure 3-37. *Technology Readiness Level of Different Hydrogen Infrastructure-Related Technologies* purchasing, efficient production processes, and standardized components to lower manufacturing costs. Reduced costs make hydrogen technologies more competitive in the market, driving their commercialization. A secure supply instills confidence in potential investors and end users, facilitating the commercialization process. Equipment standardization facilitates interoperability between different components and systems, making it easier for manufacturers and customers to integrate new technologies into existing infrastructure. Sharing best practices, research findings, and industry expertise across the supply chain stakeholders accelerates technological advancements, promotes innovation, and reduces duplication of efforts, ultimately expediting the commercialization process. A robust supply chain helps create a vibrant market for LCI H_2 technologies by fostering partnerships, encouraging investment, and facilitating market development initiatives. A favorable market environment stimulates demand and supports the commercialization of advanced and emerging technologies.

XI. SUPPORTING INFRASTRUCTURE REQUIREMENTS FOR LCI HYDROGEN

A. Introduction

Supporting infrastructure, such as CO_2 transportation and storage and the electric grid, plays a pivotal role in the development and scaling of LCI H_2 ecosystem by addressing key challenges and enabling the growth of the LCI H_2 economy.

Scaling up LCI H_2 production technologies requires the development of supporting infrastructure components like CO_2 transportation and storage. The anthropogenic carbon captured can be efficiently transported and stored by building the required CO_2 transport infrastructure, such as pipelines and large-scale geologic storage facilities to store CO_2. The development of the storage infrastructure is essential for the widespread deployment of natural gas-based LCI H_2 production facilities and makes LCI H_2 a commercially viable low-carbon energy source. A circular carbon economy can be synergistically fueled by the development of carbon utilization technologies, along with CO_2 transport, and storage.

In addition to the transportation and storage infrastructure, other supporting infrastructure to fully integrate the electric grid with the LCI H_2 ecosystem will enable enhanced energy reliability and grid resiliency. Integrating LCI H_2 into the electric grid infrastructure enables energy sector coupling and aids decarbonization efforts. The electric grid integration can promote the energy transition to a cleaner and more sustainable energy ecosystem in the United States by incorporating LCI H_2.

This section focuses on two key elements of the supporting infrastructure:

- The role of transporting and permanently storing CO_2 after it is captured at a point source from LCI H_2 production facilities in the United States
- The role of electric grid integration with LCI H_2 infrastructure and its benefits and implications to the overall electric grid reliability and resiliency

B. The Role of Carbon Dioxide Transportation and Storage Supporting Infrastructure

Under the request of former Secretary of Energy Rick Perry, the NPC developed a comprehensive assessment report titled: *Meeting the Dual Challenge: A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage* in 2019.[194] The report highlighted NPC's advice on actions needed to deploy commercial carbon management technologies at-scale into the U.S. energy and industrial marketplace. The study describes the potential role of carbon management in the United States and emphasizes its critical need in meeting the dual challenge of providing affordable, reliable energy while addressing the risks of climate change at the lowest cost. The *Meeting the Dual Challenge* report forms the basis to evaluate the CO_2 transportation and storage infrastructure to support the role and scale-up of LCI H_2 in the United States. This study incorporates the current market, regulatory trends, and CO_2 safety-related updates since the original 2019 publication.

194 National Petroleum Council. 2019. "Meeting the Dual Challenge. A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage." https://dualchallenge.npc.org/.

The role of carbon management is a critical component of the portfolio of solutions needed to meet the carbon neutrality goals of the United States by 2050. To advance the production of LCI H_2 from SMR or ATR[195, 196] (see Chapter 2: Production) at-scale to meet the future hydrogen demand in the United States, the development of supporting infrastructure to transport and store the captured CO_2 is necessary.

There is significant importance and momentum toward the role of carbon management in the United States with the passage of the IRA and the IIJA,[197] which included substantial carbon management provisions and funding of $12.1 billion over the next five years. The IIJA included the funds to build out large-scale pilot projects, to develop commercial CO_2 capture, transport, storage, and utilization infrastructure, and to authorize support for commercial-scale demonstrations, feasibility studies, DAC hubs, front-end engineering and design studies, and low-interest construction loan and grant programs. The SCALE Act (as part of the IIJA) supports the buildout of critical, regional CO_2 transport and infrastructure networks through several other programs, including financing and innovation, carbon storage validation and testing, and geologic storage permitting activities. Carbon management growth in the United States will also be driven by policy incentives like the 45Q tax credits, which has been further enhanced through the IRA offering increased federal tax incentives and making it easier to monetize 45Q credits by enabling projects to qualify for the incentives, thus driving increased public-private sector collaboration to scale carbon management infrastructure solutions in the United States. (See Chapter 6: Policy.)

195 DOE. 2023. "Hydrogen Production: Natural Gas Reforming." https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming.

196 Using either fossil based or renewable gas. According to the DOE, natural gas reforming is mature hydrogen production pathway in use today in the United States to meet the hydrogen demand across multiple end-use sectors. Today, 95% of the hydrogen produced in the United States is made by natural gas reforming in large, centralized hydrogen production facilities, https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming.

197 DeFazio, Peter A. 2021. "H.R.3684-117th Congress (2021-2022): Infrastructure Investment and Jobs Act." https://www.congress.gov/bill/117th-congress/house-bill/3684/text.

For the purposes of this study, the term "carbon management supporting infrastructure" refers to the necessary supporting infrastructure related to transporting and storing the captured CO_2, while carbon management, or CCS, often refers to the entire value chain from capturing CO_2 and transporting it to permanent storage facility. This section of the chapter evaluates the role of CO_2 transport and storage infrastructure development. See Chapter 2: Production for additional information highlighting the role of carbon capture in LCI H_2 production.

C. Carbon Dioxide Transport Supporting Infrastructure

In most cases where the CO_2 source and sink are not located within proximity of each other, the captured CO_2 will need to be transported from the capture location to a regionally dispersed storage facility. Due to the large CO_2 volumes expected to be captured at LCI H_2 production plants leveraging natural gas reformation technologies, the transportation of captured CO_2 is expected to be accomplished using pipelines operating at pressures that enable the CO_2 to remain compressed into a dense liquid or supercritical phase. While compressed CO_2 may also be transported using rail, truck, ships, and barges, pipeline is considered the most economical alternative at higher volumes and scale.[198]

CO_2 pipeline infrastructure is currently the prevalent mode of CO_2 transportation in the United States, with more than 5,000 miles of regionally dispersed and operational CO_2 pipelines (as shown in Figure 3-38). While much of the existing CO_2 transported currently is from CO_2 production wells, gaseous CO_2 captured at an LCI H_2 production facility would likely be at ambient pressure and must undergo compression prior to pipeline transport. CO_2 is most often transported as a dense or supercritical fluid (defined as well above the critical pressure at all points in the pipeline system). At these conditions, CO_2 possesses qualities of both a liquid and a gas, with a viscosity like that of a gas, but a density closer to that of a liquid. These conditions allow for higher flow

198 National Petroleum Council. 2019. "Meeting the Dual Challenge. A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage." https://dualchallenge.npc.org/.

Source: NPC, 2019, "Meeting the Dual Challenge."

Figure 3-38. *Existing CO_2 Pipelines in the United States*

rates (and lower pressure drops) than if CO_2 were transported as a gas without the compromise of lower throughput due to its liquid-like density. Pipeline pressure requirements are set to ensure that the operating pressure is safely above its critical pressure.

Several key infrastructure elements are required for the transportation of CO_2 using pipelines after it is captured at a hydrogen production facility not colocated with a storage/utilization site. Captured CO_2 is initially compressed and treated to remove water to ensure it meets pipeline specifications for injection into the pipeline. Gathering pipelines may also be necessary to connect several nearby sources to a centralized compression facility prior to injection into the main trunkline. Intermediate compression stations may be required to move the CO_2 through the pipeline network to its destination. These stations may include pumps, compressors, and control systems. CO_2 pipelines made of steel or high-density polyethylene are designed to withstand the high-pressure and temperature changes associated with transporting CO_2. CO_2 pipelines are most often buried underground and are equipped with valves and other control systems to ensure the safe and efficient transport of CO_2. Receiving terminals at the end of the pipeline are used to transfer the CO_2 to tanker trucks or railcars for further transportation for industrial utilization, or to storage facilities.

As mentioned in the beginning of this subsection, CO_2 can also be transported via truck, rail, ship, and barge. Transport of CO_2 by truck and rail is viable for small quantities, from 4 MT to a few hundred metric tons. Trucks can also be used at some project sites, moving the captured CO_2 to a nearby storage or utilization location. Ship transport of CO_2 occurs on a small scale in Europe, carrying approximately 1,000 MT of food-grade CO_2 from large point sources to coastal distribution terminals. Although transport of liquefied gases via barge is possible, dense phase CO_2 has not been transported by barge (primarily due to a lack of demand for barge movement).

Given the large volumes of CO_2 that need to be captured, as storage infrastructure is deployed at-scale in the longer term, transport of CO_2 by truck and rail, although possible, may not be economical. The cost of CO_2 transport by truck and rail ranges from 3x-10x[199] more than pipeline transport on a unit basis (due to the large economies of scale offered by pipelines). However, truck and rail transport could provide more flexibility for isolated point-to-point value chain solutions.

With the potential deployment of nationwide hydrogen and carbon management efforts, DOE has emphasized the need of common carrier transport and storage infrastructure in the near term focusing on projects in industries with high-purity CO_2 streams, including hydrogen.[200] IIJA funding offers additional support through programs such as the Carbon Storage Validation and Testing ($2.5 billion) and Carbon Dioxide Transportation Infrastructure Finance and Innovation ($2.1 billion) to support common carrier projects. Given the expected CO_2 volumes that would be potentially captured from the production of LCI H_2 at large concentrated point sources, along with the potential for clustering of hydrogen hubs, CO_2 pipeline has the potential to offer the most economical mode of transporting CO_2 from capture sources to storage sites.[201]

D. Carbon Dioxide Storage Infrastructure

Compressed CO_2 is safely, securely, and permanently stored by injecting it into carefully selected subsurface geologic formations (saline deposits, depleted oil and gas reservoirs, and un-minable coal seams). The United States is endowed with CO_2 geologic storage capabilities.[202] As illustrated in Figure 3-39, the majority of the Lower 48 states offer an abundance of subsurface CO_2 storage potential. Although there are varying estimates of the CO_2 storage capacity potential, experts generally agree that it is enough to store hundreds of years' worth of CO_2 emissions captured from anthropogenic sources. According to the National Energy Technology Laboratory in 2015, assessments indicate that the United States may have average total technical storage resources ranging from 3,000 to 8,600 billion metric tons.

Geologic storage involves the process of injecting CO_2 into a secure underground geologic formation. The development of CO_2 geologic storage projects depends on selecting geologic formations that offer sufficient pore space (porosity) and depth. The formation rock must have enough pore space for the CO_2 to be contained within the formation. These criteria are met by sedimentary rocks formed over millions of years as small grains of sediment accumulated on seashores, deltas, ocean floors, riverbeds, and lakes. The formations must also be deep enough (3,000 ft and below) to store the CO_2 as a dense fluid under natural pressure and temperature. Geologic seal is an essential determinant for ensuring that the CO_2 injected into a geologic formation remains trapped and does not migrate into groundwater or the atmosphere. The seal rock must be sufficiently impermeable to prevent the CO_2 from migrating, but it must also be permeable enough to allow the CO_2 to be injected into the geologic formation. The assessment of the seal capacity, geometry, and integrity is an important part of the planning and development of storage projects. By understanding the properties of the seal rock, project developers can ensure that the CO_2 is safely and permanently stored underground.

1. Storage Geology

CO_2 storage reservoirs are divided into conventional and unconventional reservoirs. Conventional formations have rock and fluid characteristics that enable gas and fluid to easily flow to or from wellbores drilled into the formation. The rock types that facilitate this include sandstone, limestone, dolomite, or a mixture of these rock types. Unconventional formations include a collection of rock types such as shale, and low-permeability (tight) sandstones, and some

199 DOE. 2023. "Pathways to Commercial Liftoff: Clean Hydrogen." https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-Clean-H_2-vPUB.pdf.

200 DOE. 2023. "Pathways to Commercial Liftoff: Clean Hydrogen." https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-Clean-H_2-vPUB.pdf.

201 Project specific circumstances should be evaluated to confirm this presumption.

202 Kearns, J., Teletzke, G., Palmer, J., Thomann, H., Kheshgi, H., Chen, Y.H., Paltsev, S., and Herzog, H. 2017. "Developing a Consistent Database for Regional Geologic CO_2 Storage Capacity Worldwide." *Energy Procedia*. 114 (July): 4697–4709. https://doi.org/10.1016/j.egypro.2017.03.1603.

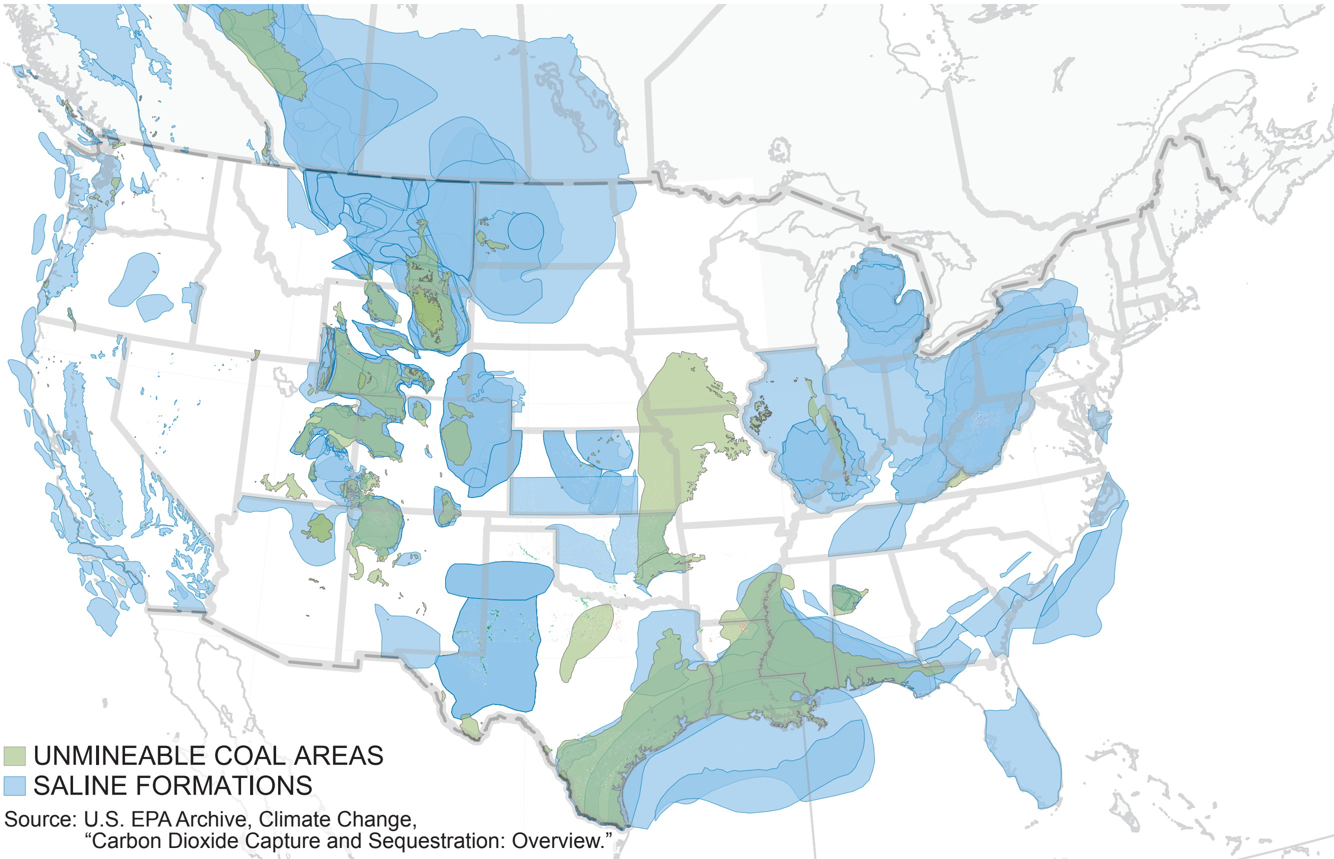


Figure 3-39. U.S. Assessment of Geologic CO_2 Storage Potential

carbonates. Other possible subsurface CO_2 storage options also include coal beds and basaltic and ultramafic rocks.

Conventional geologic formations: Storing CO_2 in conventional formations can utilize one of several trapping processes: buoyant, residual, solubility, and mineral. Buoyant trapping utilizes the behavior of CO_2 to flow upward slowly until it is immobilized in a stratigraphic trap formed by the geologic seal. Residual trapping occurs as small droplets of CO_2 are left behind during the migration of a CO_2 plume through the porous reservoir rock. Solubility trapping dissolves a fraction of CO_2 instantly when it is injected into the formation. Mineral trapping, which is considered one of the slowest forms of trapping, involves CO_2 reacting with the minerals in the reservoir.

Unconventional geologic formations: Storing CO_2 in unconventional formations composed of low-permeability rocks containing hydrocarbons may require horizontal drilling and hydraulic fracturing.

Depleted hydrocarbon reservoirs: Storing CO_2 in depleted hydrocarbon reservoirs can be advantageous for the following reasons: 1) well-known and characterized reservoir properties, 2) established trapping and sealing mechanisms of buoyant fluids in structural and stratigraphic traps, 3) potential trapping of CO_2 in remaining oil and water rather than remaining as a separate phase, 4) reservoirs with weak water drive may deplete pressure to further enhance storage capacity, and 5) use of existing oilfield infrastructure such as wells. However, there are also several technical challenges to using depleted oil fields for CO_2 storage. During primary oil production, oil fields undergo large changes in stress that may permanently reduce the pore volume of the rock. Permeations of numerous stratigraphic intervals caused by oil wells, and the wells themselves, may also provide potential conduits for CO_2 to leak from the reservoir. Lastly, proper modeling of multiphase flows in wells is necessary to ensure that Joule-Thomson effects in the wellbore do not lead to extreme cold temperatures that could damage the well.

Other storage options: Other options include CO_2 injection and storage in deep subsurface coal beds or CO_2 mineralization to form solid carbonate phases in basaltic and ultramafic rocks and mine tailings.

E. Safety of Carbon Dioxide Transportation and Storage Infrastructure

As with other oil and gas infrastructure projects, safety is a critical element to consider in the design, construction, and operation of any storage infrastructure. As a relatively new value chain, CO_2 transportation and storage require an emphasis on safety to encourage widespread adoption and acceptance of the communities it affects.

1. Safety of Carbon Dioxide Transportation

CO_2 pipelines have been safely and reliably transporting CO_2 in the United States since 1972, with the first CO_2 pipeline built in West Texas called Canyon Reef Carriers Pipeline. CO_2 pipelines in the United States are regulated under Title 49 CFR Part 195, Transportation of Hazardous Liquids by Pipeline, which applies to the transportation of hazardous liquids and carbon dioxide.

Under the U.S. DOT, PHMSA is responsible for regulating the movements of all hazardous materials in the United States, including pipelines. PHMSA sets the standards for safe construction and operation of CO_2 pipelines, including technical design specifications and the requirements for mechanical integrity management.

Commercial CO_2 pipelines operate at pressures between 80 and 150 bar, a higher pressure than most natural gas transmission pipelines. In this operating pressure range, CO_2 is a dense phase fluid, which allows for a higher flow rate than gaseous CO_2. Additionally, dense phase CO_2 behaves more like a liquid (in terms of its flow capacity) and can be transported using higher efficiency pumps instead of gas compressors to recover pressure losses (elevation changes and friction) in the pipeline.

CO_2 composition quality specifications have been established to avoid pipeline corrosion in accordance with PHMSA regulations. Corrosiveness is largely dependent on the presence of water in the CO_2 stream; therefore, CO_2 is often dehydrated before injection into pipelines. Oxygen and hydrogen sulfide concentrations are also managed to minimize corrosion or stress cracking. External coatings and cathodic protection are often used to protect the pipelines from external corrosion. In summary, the critical issues for CO_2 transport include:

- Safety and presence of hazardous substances in the CO_2 stream
- Avoidance of free (liquid) water formation
- Avoidance of hydrate formation
- Avoidance of corrosion or stress cracking
- Reduction of the CO_2 volume (increased density, which increases transport capacity)

On May 26, 2022, PHMSA announced new safety measures on CO_2 pipelines after the pipeline leak incident on February 22, 2020, in which a CO_2 pipeline failed approximately one mile southeast of Satartia, Mississippi, and around 30,000 barrels of liquid CO_2 immediately began to vaporize at atmospheric conditions. It was found that the pipeline failed on a steep embankment, which had subsided adjacent to a local highway and heavy rains were believed to have triggered a landslide, which created axial strain on the pipeline and resulted in a full circumferential girth weld failure. PHMSA has completed a failure investigation report and seeks to address specific measures to update standards for CO_2 pipelines, including requirements related to emergency preparedness and response.[203]

2. Safety of Carbon Dioxide Storage

As described in the CO_2 storage section (Section XI.D), a potential storage reservoir must have a

203 DOT PHMSA. 2022. "PHMSA Announces New Safety Measures to Protect Americans from Carbon Dioxide Pipeline Failures after Satartia, MS Leak." https://www.phmsa.dot.gov/news/phmsa-announces-new-safety-measures-protect-americans-carbon-dioxide-pipeline-failuress.

geologic seal above it. The sedimentary rock of the seal should have low permeability to prevent the CO_2 from leaving the storage formation. Additionally, the process of CO_2 injection into the formation rock displaces saline water in the formation, causing the reservoir's fluid pressure to increase. The extent of this increase is a function of 1) the geologic permeability, 2) the size of the storage reservoir, and 3) the CO_2 injection rate. Any storage safety concerns, such as the risk of damaging the reservoir and causing CO_2 leakage, should be carefully considered during the design and engineering phase and carefully monitored (i.e., plume modeling) continuously during the life of the CO_2 storage.

3. Carbon Dioxide Leakage

CO_2 leakage is an important safety topic that needs to be carefully analyzed and considered, across design, construction, and operation of any CO_2 pipeline and storage project.

As discussed, PHMSA is proactively implementing new measures to reinforce its safety oversight of CO_2 pipelines and protect communities from potential pipeline failure. Robust leak detection monitoring systems along the CO_2 pipeline route can help monitor potential CO_2 leakage.

Storage sites typically monitor for a CO_2 plume to confirm that the injected CO_2 stays stored and does not breach the reservoir seal. The design intent is for the sealing formations to prevent the CO_2 from migrating into shallower groundwater aquifers, or to the surface where it could be released to the atmosphere, defeating the purpose of having stored it. Careful site evaluation and selection are conducted to avoid any permeable fault or fracture in the seal, or a leaky wellbore, and for other considerations to ensure that the CO_2 remains trapped and permanently stored. In practice, the plume is tracked for new storage sites for lateral and vertical migration until the plume stops its migration. Remote monitoring is crucial for tracking CO_2 plume migration and detecting leaks during and after injection. It could also involve monitoring plume boundaries and verifying volume, although regulations differ between states as to whether it is okay to stop monitoring after the plume stops moving.

F. Electric Grid Integration with LCI Hydrogen Infrastructure

The electric grid infrastructure plays a critical and synergistic role with the development and scaling of LCI H_2 infrastructure. The need for large and stable electricity demand loads for LCI H_2 production from electrolysis would necessitate electric grid interconnection. As the electric grid integrates over time with LCI H_2 infrastructure, it will facilitate further integration of renewable energy sources into the grid to support the growing demand for renewable electricity. The coupling of renewable energy for LCI H_2 production utilizing the electric grid also offers the potential to increase the utilization rates of electrolyzers and to reduce the cost of the hydrogen production.

As illustrated in Figure 3-40, the growing interdependence of multiple energy subsector infrastructures to meet decarbonization needs means that impacts on one sector can have a cascading effect on the other, posing challenges to the overall energy system resiliency and reliability under loss of load expectations. In addition to supporting higher levels of direct electrification across multiple end-use sectors, these interdependencies are likely to grow significantly. As a result, it is critical for industry participants and regulators to understand the interdependence and interoperability of the electric grid with other energy subsectors.

Electric grid integration with LCI H_2 infrastructure also enables energy storage and load balancing capabilities (see Chapter 5: Demand). Excess electricity from the grid, particularly during periods of low demand or high renewable energy generation, can assist with LCI H_2 production hydrogen through electrolysis. The produced LCI H_2 can then be stored and later converted back to electricity when demand exceeds supply, helping balance the grid load and ensuring a stable and reliable power supply. LCI H_2 infrastructure, in turn, can support additional firm dispatchable power needs during periods of high demand, such as hot summer days or extreme weather events when the grid might face strain. Stored LCI H_2 acts as a backup power source, ensuring the availability of reliable

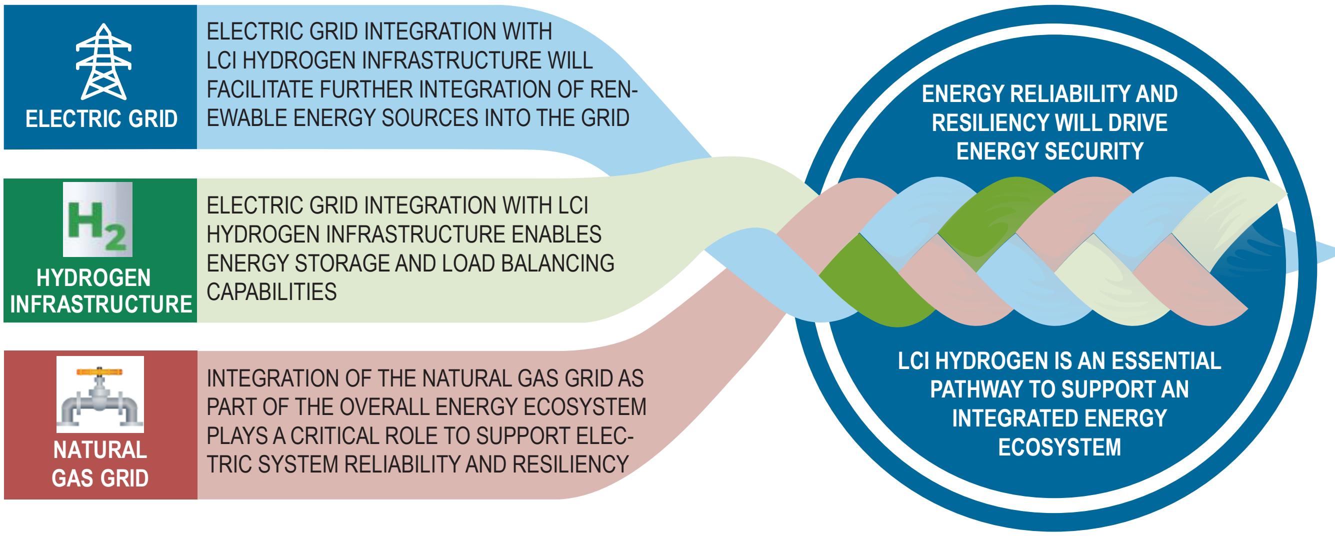


Figure 3-40. *Energy Reliability and Resiliency with an Integrated LCI Hydrogen Infrastructure Will Drive Energy Security*

electricity supply in emergency situations and enhancing the overall resilience of the electric grid. Hydrogen fueled power generation can be ramped up or down quickly, providing rapid response to changes in electricity demand and grid frequency fluctuations. This flexibility helps maintain grid stability, especially when dealing with intermittent renewable energy sources and variations in electricity demand.

LCI H_2 can also be used to generate electricity through fuel cells or combustion turbines, serving as a backup power source. This enhances the reliability of the electric grid during critical periods. By utilizing hydrogen-based power generation, such as fuel cells, critical facilities and infrastructure can continue to operate during grid disruptions or blackouts. By decentralizing LCI H_2 production and utilizing it locally, the need for long-distance transmission of electricity can be reduced. This can minimize transmission losses and congestion on the grid, enhancing its overall efficiency and reliability.

Successful integration of LCI H_2 infrastructure with the electric grid will require appropriate planning, coordination, and optimization. Considerations such as infrastructure development of LCI H_2 production capacity, long-duration storage capabilities, and efficient conversion technologies, are essential to maximize the benefits and minimize potential challenges associated with grid integration. Timely integration of large flexible loads will be difficult but necessary to support the rapid growth in electricity demand. System operators and asset owners must work together to coordinate infrastructure expansion and encourage new loads to provide useful and necessary ancillary services to meet reliability requirements. Coordination of existing and new loads with grid additions is critical for reliability, but it requires complex multiparty coordination and collaboration.

Defining the reliability standards needed (such as the North American Electric Reliability Corporation (NERC)) using a reliability-based approach that focuses on performance, risk management, and system capabilities to address energy resilience across various regional domains (e.g., WECC, CAISO, etc.) are crucial when integrating LCI H_2 as part of energy sector coupling with the electric grid in the United States. NERC is responsible for ensuring the reliability and security of the North American bulk power system, and its reliability standards are designed to maintain a stable and resilient grid. LCI H_2 integration will introduce new dynamics to the electric grid, such as LCI H_2 production using load from the electric grid, available LCI H_2 storage capacity, and reconversion back to electricity based on load demand requirements from the electric grid. Compliance with NERC reliability standards helps ensure that sector coupling is integrated in a manner that does not compromise the stability and resiliency of the electric grid. By adhering to NERC standards, the potential impacts of LCI H_2 integration on grid operations, voltage control, frequency regulation, and other critical parameters can be effectively managed.

Integrating LCI H_2 into the electric grid requires careful consideration of the infrastructure, transmission capacity, interconnections, and operational requirements. Compliance with NERC standards will help electric utilities and stakeholders in their planning and operational decision-making processes and will ensure that the grid can effectively accommodate the integration of LCI H_2 and maintain reliable power supply. As LCI H_2 production facilities, such as electrolyzers or fuel cells, are interconnected with the electric grid, compliance with the NERC standards helps ensure that the grid interconnection process is conducted safely and reliably. NERC compliance will include considerations for electric grid interconnection studies, equipment performance, protection systems, and operational coordination to maintain system stability and prevent disruptions.

Grid Enhancing Technologies (GETs) have the potential to enhance operations and planning of electric transmission capacities and help unlock the grid interconnection queues necessary for serving and receiving electric loads. Technologies include Dynamic Line Ratings that enable thermal rating adjustments of the electric transmission systems based on weather conditions, Advanced Power Flow Control Systems to manage overload system conditions, and Topology Optimization Controls to assist in reconfiguration or rerouting of power flow around overloaded or congested grid areas.[204]

204 Caspary, Jay, and T. Bruce Tsuchida. 2021. "Unlocking the Queue with Grid Enhancing Technologies: Case Study-Southwest Power Tool Study Approach." https://www.brattle.com/wp-content/uploads/2021/06/21200_unlocking_the_queue_with_grid_enhancing_technologies.pdf.

In addition to GETs, performing power flow modeling will be essential to address NERC reliability standards when integrating LCI H_2 and the electric grid. Power flow modeling involves simulating and analyzing the behavior of electrical power systems to understand the flow of electricity, voltage levels, and system stability. By simulating the integration of LCI H_2 infrastructure and associated loads, power flow analysis can determine the system capacity and adequacy of the grid to meet the supply and demand loads and address potential constraints. Contingency analysis can help identify potential system vulnerabilities, assess the impact of electric system failures driving the loss of load expectation (LOLE), and analyze the ability of the grid resiliency to maintain reliable power supply. Addressing LOLE in the context of LCI H_2 integration is crucial to maintain electric system reliability and resilience. By ensuring adequate generation capacity, balancing supply, and demand, enhancing grid flexibility, conducting comprehensive system adequacy studies, improving forecasting and modeling, and implementing robust contingency planning, stakeholders can minimize the risk of LOLE and support a reliable and resilient electric grid as LCI H_2 becomes a more integral part of the energy system.

Evaluating the future energy system planning and integration scenarios of the electric grid and the LCI H_2 infrastructure at the regional level requires complex and data-intensive power flow modeling framework to simulate for hourly energy supply and dispatch variability in the overall system informing electric demand and supply optimization within the model. Incorporating production cost models (akin to the electric system's integrated resource planning models) given a set of generating resources, loads, weather, and dispatch constraints to address reliability of the energy system adds further complexity. This is an unrealized evaluation as part of the current study and needs further attention as part of the subsequent independent evaluation, since it offers the potential to evaluate the role of LCI H_2's benefits as part of the overall energy ecosystem.