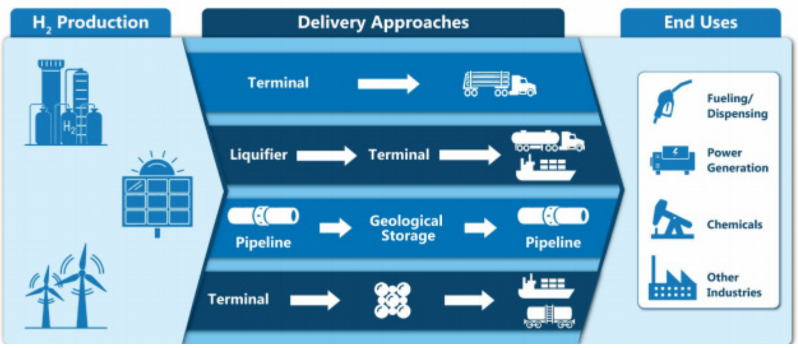
CLEAN HYDROGEN TRANSPORTATION AND DELIVERY

Hydrogen can be used to move, and deliver clean energy to where it is needed. Today, hydrogen is transported from the point of production to the point of use via pipeline, over the road in cryogenic liquid tanker trucks or gaseous tube trailers, by rail or barge, and using chemical hydrogen carriers. Hydrogen used in portable or stationary applications can be delivered by truck to a storage facility or in cylinders, similar to the propane used for gas grills, or in cartridges that would resemble a battery. The technologies required to support these delivery pathways are at various stages of development, but they must ultimately be both affordable and meet or exceed the level of safety, convenience, reliability, and energy efficiency expected from existing infrastructure used for other fuels for clean hydrogen to become a replacement fuel.



The four main methods of hydrogen delivery: gaseous tube trailers, liquid tankers, pipelines, and chemical hydrogen carriers

Hydrogen Pipelines. The United States has over 1,600 miles of hydrogen pipelines and three caverns that have the capacity to store thousands of metric tons of hydrogen. By contrast, there is about 2 million miles of natural gas distribution mains and pipelines in the U.S. currently. Hydrogen pipelines are often used in regions where there is significant demand and that demand is expected to remain stable for a long period of time. This is because hydrogen pipelines are capital intensive, but when the quantity of hydrogen demand is high, they have a lower levelized cost over time. While pipelines are the most energy-efficient approach to transporting hydrogen, their deployment is challenged by their high capital costs.

Chemical Hydrogen Carriers. Another emerging method to transport large amounts of hydrogen is the use of chemical hydrogen carriers, which are liquid- or solid-phase materials that can chemically bond with hydrogen to "carry" it at low-pressure and can then release the hydrogen on demand. They offer the potential for significantly higher energy density compared with gaseous or even liquid hydrogen transport, reducing hydrogen delivery costs. The most common form of a chemical hydrogen carrier is ammonia.

Hydrogen Dispensing and Fueling. Once hydrogen is transported to the site of use, it may need to be conditioned by pressurizing, cooling, or purification, and it is commonly stored on-site in bulk. These processes can involve a number of different systems—for example, hydrogen fueling stations for hydrogen used in fuel cell electric vehicles.

Transportation/Delivery Challenges

Delivery technology for hydrogen infrastructure is currently available commercially, and several U.S. companies deliver bulk hydrogen today. Some of the infrastructure is already in place because hydrogen has long been used in industrial applications, but existing infrastructure is not sufficient to support widespread use of hydrogen as an energy carrier. Because hydrogen has a relatively low volumetric energy density, its transportation, storage, and final delivery to the point of use increases the cost for it as an energy resource and result in some of the energy inefficiencies associated with using it as an energy carrier.

The key challenges to hydrogen delivery include reducing delivery costs, increasing energy efficiency, maintaining hydrogen purity, and minimizing hydrogen leakage. Further research is needed to analyze the trade-offs between the hydrogen production options and the hydrogen delivery options when considered together as a system.

It will also take time to develop a national hydrogen delivery infrastructure and will likely include combinations of various technologies. Delivery infrastructure needs and resources will vary by region and type of market: urban, interstate, or rural. Infrastructure options will also evolve as the demand for hydrogen grows and as delivery technologies develop and improve.

Transportation/Delivery Needs:

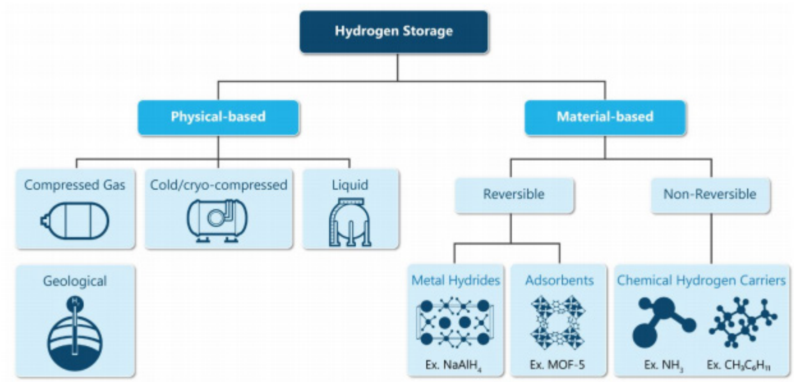
- Lower-cost and more-reliable systems for distributing and dispensing hydrogen
- Research on utilizing existing natural gas pipelines to transport hydrogen
- Advanced technologies and concepts for hydrogen distribution including liquefaction and material based chemical carriers
- Rights-of-way, permitting, and reduced investment risk of deploying delivery infrastructure
- Materials compatibility with hydrogen at high pressures and/or low temperatures
- Innovations in hydrogen liquefaction
- Innovative components for low-cost distribution and dispensing

Information and graphics courtesy of the U.S. Department of Energy's 2020 Hydrogen Program Plan unless otherwise noted.

CLEAN HYDROGEN STORAGE

Hydrogen has nearly three times the energy content of gasoline per unit of mass, but the volumetric energy ensity of gaseous hydrogen is low, making it difficult to store in compact containers. To overcome this challenge, hydrogen is usually stored using physical processes, as a gas or cryogenic liquid; it can also be stored using material-based processes that incorporate hydrogen in chemical compounds.

Physical-based Storage. Gaseous hydrogen is typically stored in metal, pressurized tanks for transportation and other stationary and power generation applications. Large-scale geologic storage within salt caverns, saline aquifers, depleted natural gas or oil reservoirs, and engineered hard rock reservoirs offers opportunities for long-duration energy storage applications. One example is the industrial-scale hydrogenstorage salt cavern located in Beaumont, Texas, which currently serves as a buffer in the Gulf Coast hydrogen pipeline system. More research is needed to reduce the cost and ensure the safety of gaseous hydrogen storage.



Current portfolio of hydrogen storage options. Includes physical-based gaseous and liquid sotrage in tanks, and reversible and non-reversible materials-based sotrage. Approaches for large-scale bulk storage (such as geological storage) are also under investigation.

Material-based Storage. Clean hydrogen can also be densely stored at low pressures in certain material compounds. Different categories include metal hydrides, adsorbents, and chemical hydrogen storage. Metal hydrides store hydrogen atoms by chemically bonding them to atoms in the compound structure, such as magnesium borohydride. Adsorbents utilize weak bonding between molecular hydrogen and adsorbent surfaces, and typically require lower storage temperatures. Hydrogen storage via metal hydrides and adsorbents is considered reversible, since hydrogen uptake and release can be controlled by changing the temperature and/or the pressure. Many chemical hydrogen carriers (as discussed in our transportation fact sheet, such as ammonia) have the potential to store large quantities of hydrogen by mass and volume. With these chemcial carriers, thermal or catalytic chemical reactions are needed both to bind and release the hydrogen, and these processes can result in significant round-trip energy losses. Currently no material-based storage approaches are commercially mature, and foundational material and system-level RD&D are needed for the discovery and optimization of viable hydrogen storage materials capable of achieving the cost,energy density, and hydrogen uptake and release required for commercialization.

Storage Needs and Challenges:

- Lower-cost hydrogen storage systems
- Higher storage capacity, with reduced weight and volume
- Large-scale storage, including onsite bulk emergency supply and in geologic formations
- Optimized storage strategies for co-locating stored hydrogen with end-use applications to meet throughput and dynamic response requirements and reduce investment cost
- Materials compatible with hydrogen for durability and safety
- Cryogenic RD&D for liquid hydrogen and cold/cryo-compressed storage
- Discovery and optimization of hydrogen storage materials to meet weight, volume, kinetics, and other performance requirements
- Optimization for round-trip efficiency using chemical hydrogen carriers
- Storage of hydrogen in the form of a chemical energy carrier that can be used in hydrogen turbines
- Identification, assessment, and demonstration of geologic storage of hydrogen